Designing Electronic Systems for the Space Radiation Environment: An Overview

Kenneth A. LaBel

Radiation Effects and Analysis Group Leader

Electronics Radiation Characterization Project Manager

Living with a Star Space Environment Testbed Experiments Manager

ken.label@gsfc.nasa.gov

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Abstract

- In this talk, we will discuss the implications of the natural space radiation environment on spacecraft systems with a focus on microelectronic and photonic technologies. Included topic areas are
  - A review of the environment and basic effects on technologies,
  - Concerns over emerging technologies, and,
  - System level method for radiation hardness assurance (RHA) including a discussion of mitigative approaches.

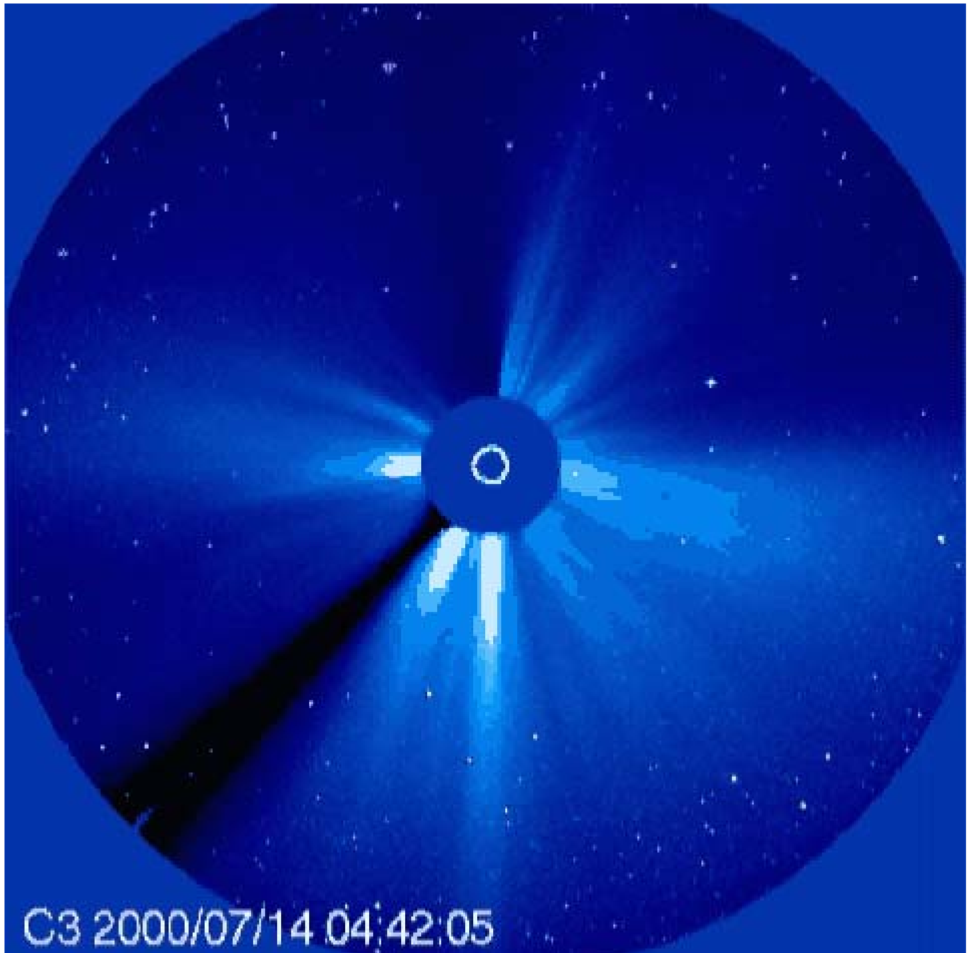
Outline

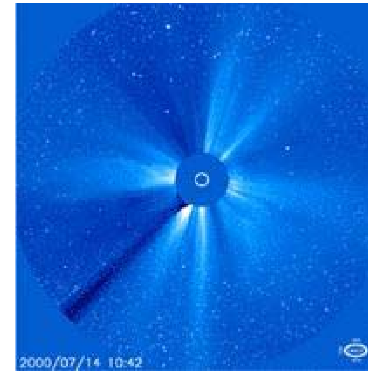
- Introduction
  - Why radiation is a concern for modern space systems
- The Natural Space Radiation Environment
- Basic Radiation Effects
- NASA and Radiation Requirements
- Radiation and Technology
- System Level Approach to Radiation Hardness Assurance (RHA)
- Mitigating Radiation Effects in Electronics
- Ground-based Radiation Effects Research: Recent Highlights
- Final Comments

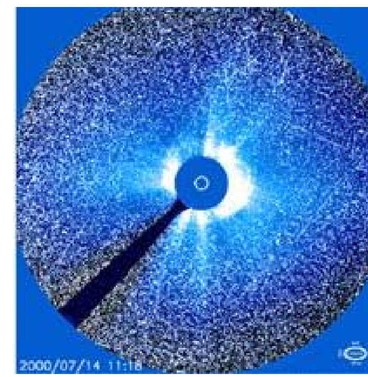
Introduction

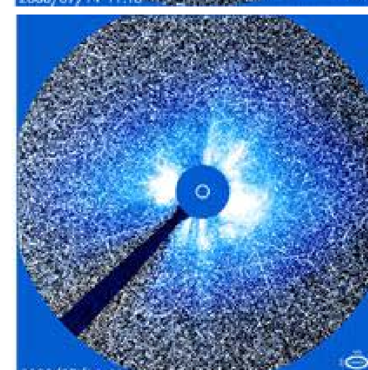
SOHO/LASCO C3

July 14, 2000









Radiation May Affect:

- Microelectronics*
- Photonics*
- Materials
- Coatings/epoxies/etc.
- Humans/biological systems

Focus of this talk

Spacecraft Design Reality

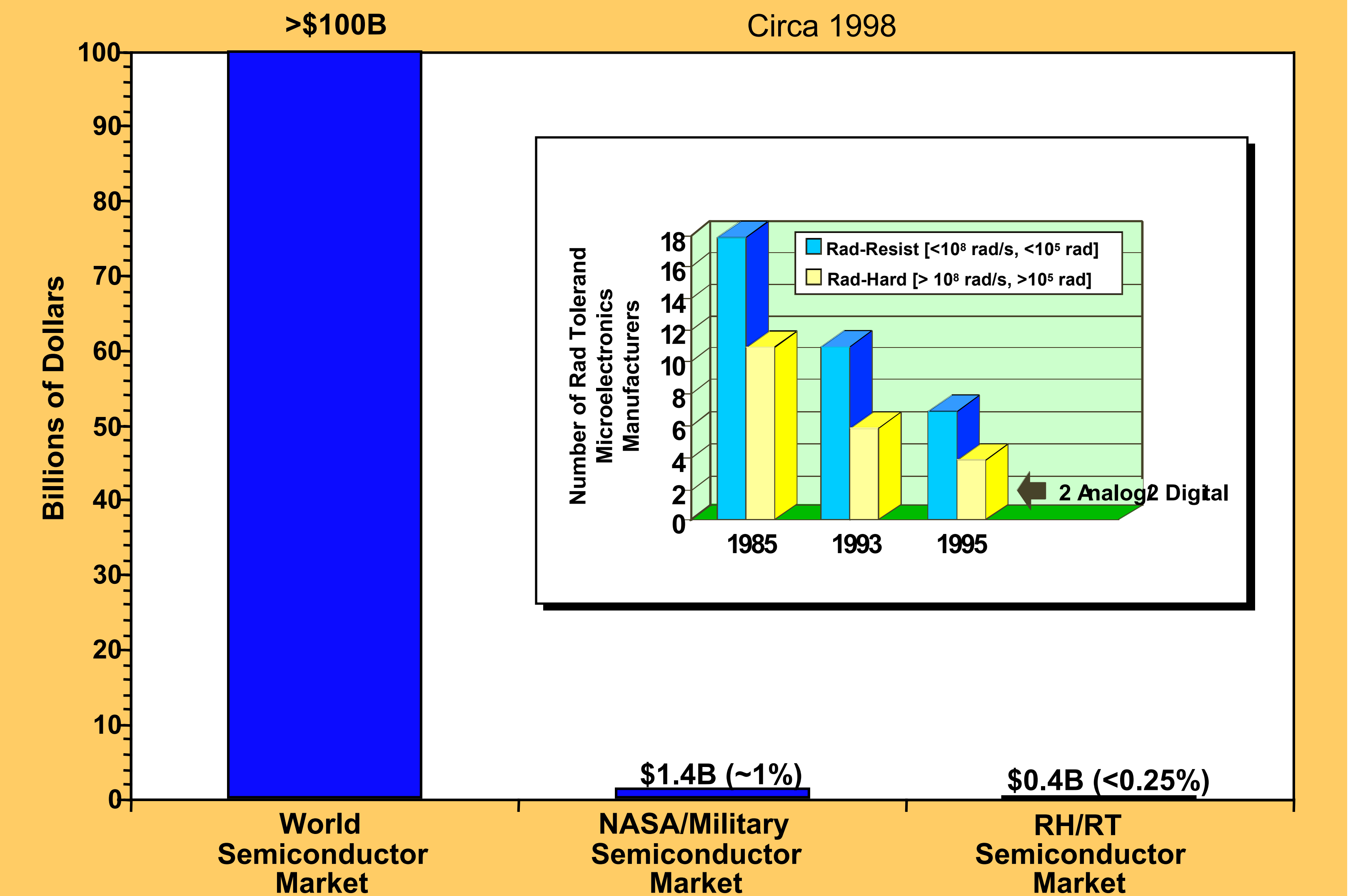
Programmatic Considerations:

- Reduced Cost
- Use of Flight Heritage Designs
- Mass-Buy Procurement
- Decreased Procurement Lead Times
- Overlapping Development Schedules
- Reduced Manpower

Technical Considerations:

- Reduced Weight
- Reduced Power Consumption
- Increased Performance Requirements
- Increasingly Complex Sensor Arrays
- **Decreased Availability of Rad-hard Devices**

The Space Semiconductor Market - Reduced Options for Risk Avoidance



Increased Radiation Awareness - Three Prime Technical Drivers

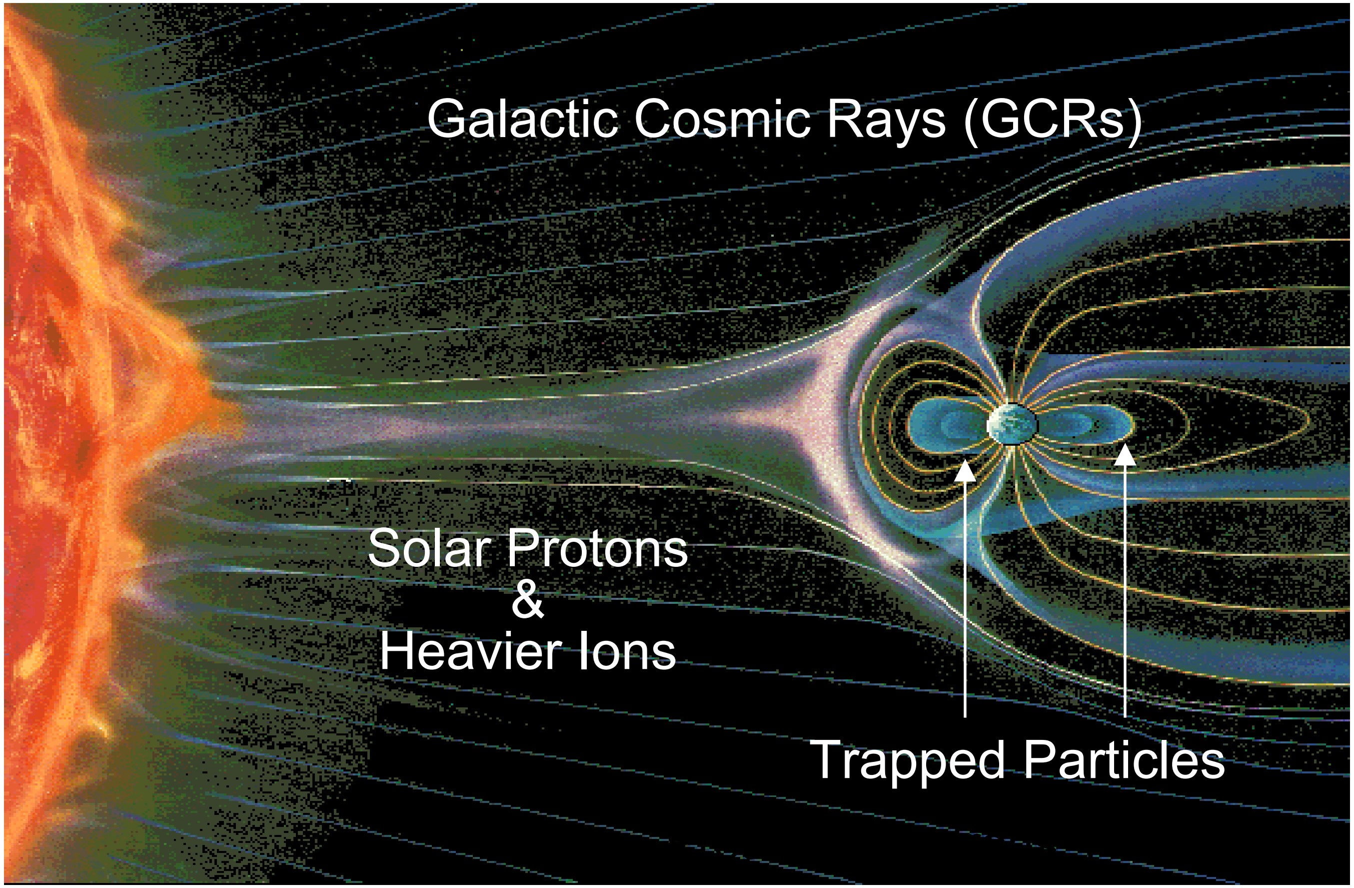
- Commercial and emerging technology devices are more susceptible (and in some cases have new radiation effects) than their predecessors.
  - Limited radiation hardened device availability
- There is much greater uncertainty about radiation hardness because of limited control and frequent process changes associated with commercial processes.
- With a minimization of spacecraft size and the use of composite structures,
  - Amount of effective shielding against the radiation environment has been greatly reduced, increasing the internal environment at the device.
- **THESE THREE DRIVERS IMPLY THAT WE ARE USING MORE RADIATION SENSITIVE DEVICES WITH LESS PROTECTION.**

Sample Microelectronics Issue Affecting Spacecraft

- Use of Ultra-Low Power (ULP) Electronics
  - Reduces spacecraft power consumption requirements
  - Requires reduced solar arrays and batteries
  - Reduces thermal loads which in turn require reduced structural housing
- Overall effect:
  - Orders of magnitude reduction in size/mass/power and cost
  - Radiation risks?

The Natural Space Radiation Environment

Space Radiation Environment

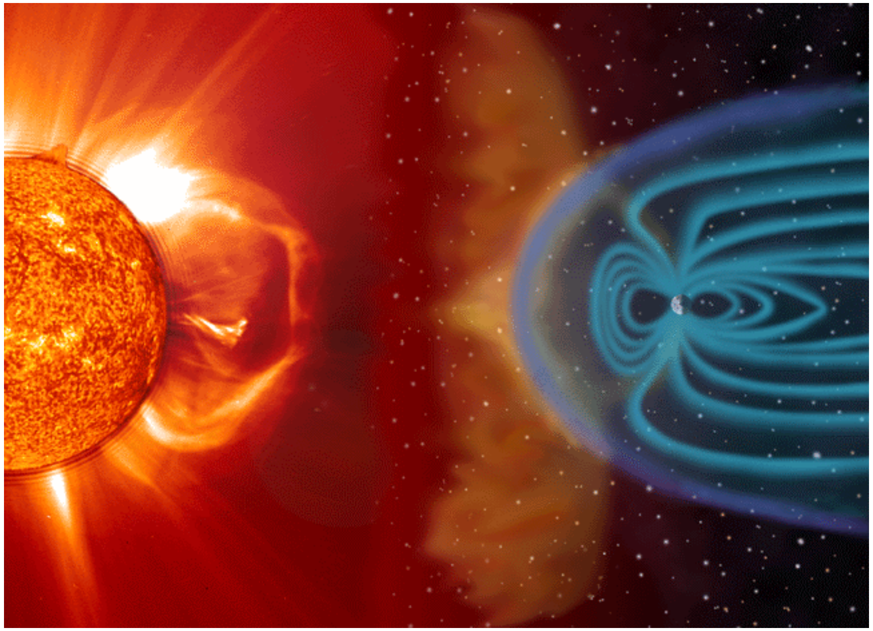


Nikkei Science, Inc. of Japan, by K. Endo

Janet Barth http://radhome.gsfc.nasa.gov/radhome/papers/apl_922.pdf

Sun: Dominates the Environment

A True Dynamic System



Source

Protons

Heavier Ions

Trapped Particles

Modulator

Galactic Cosmic Rays

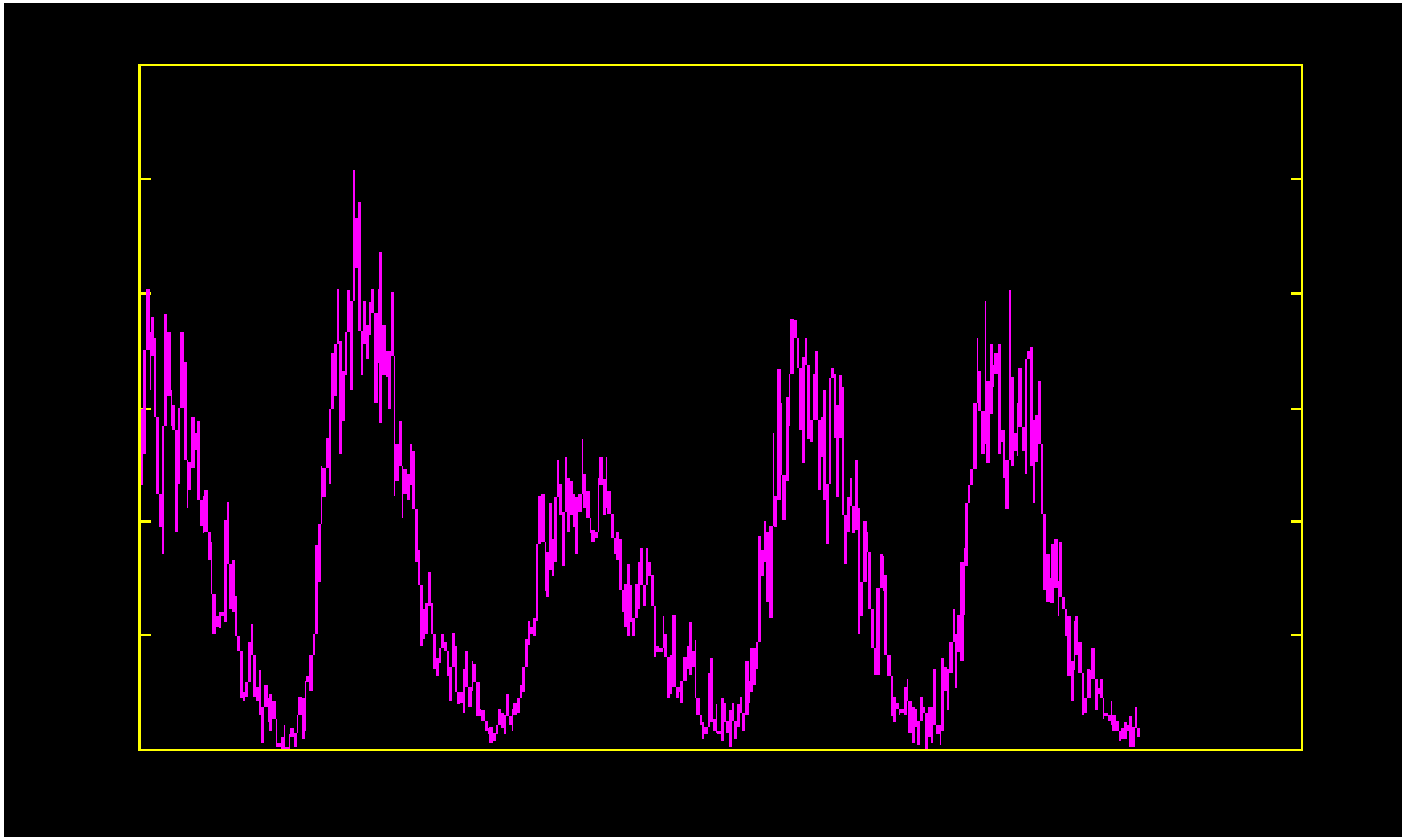
Atmospheric Neutrons

Trapped Particles

Sunspot Cycle

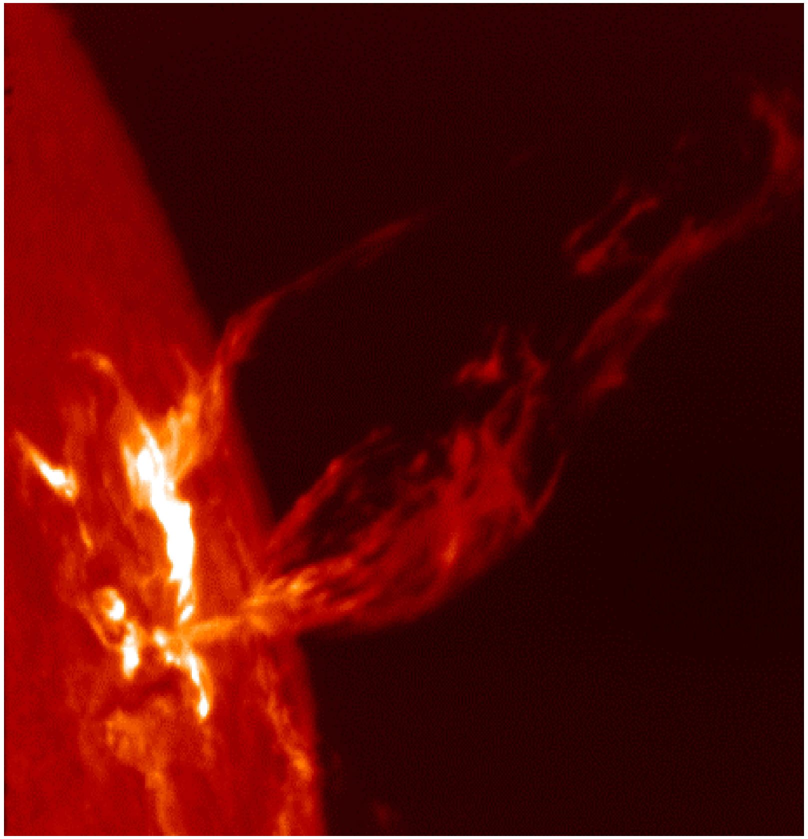
after Lund Observatory

Sunspot Numbers



Length Varies from 9 - 13 Years
7 Years Solar Maximum, 4 Years Solar Minimum

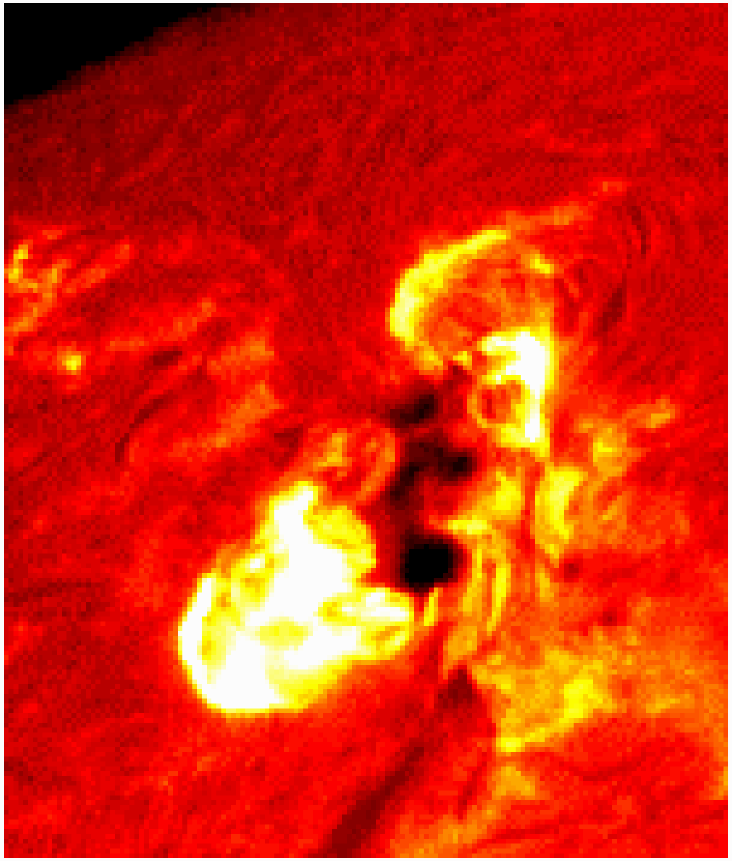
Gradual Solar Events



Holloman AFB/SOON

- Coronal Mass Ejections (CMEs)
- Particles Accelerated by Shock Wave
- ***Largest Proton Events***
- Decay of X-Ray Emission Occurs Over Several Hours
- Large Distribution in Solar Longitude

Impulsive Solar Events

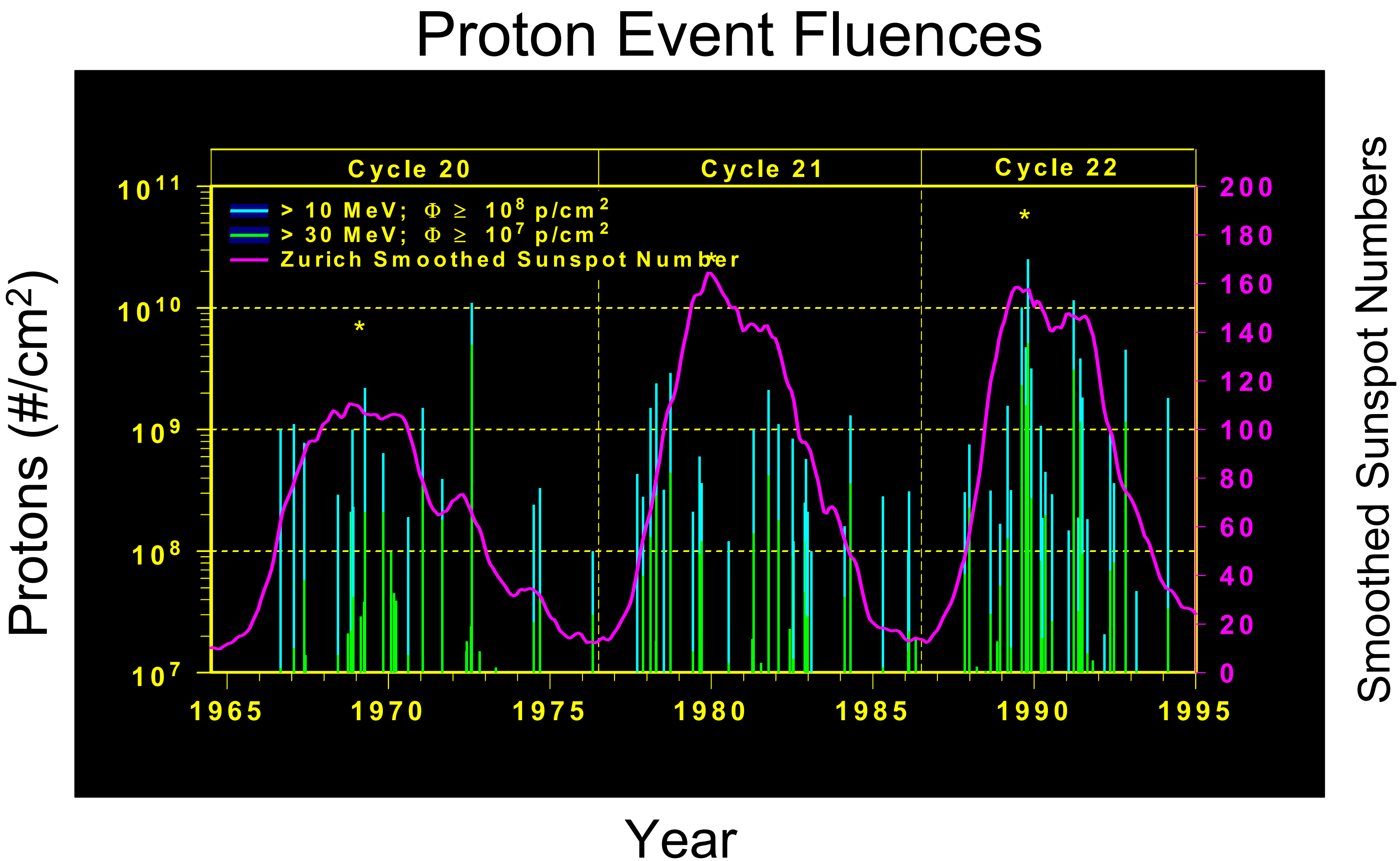


- Solar Flares
- Particles Accelerated Directly
- Heavy Ion Rich
- Sharp Peak in X-Ray Emission
- Concentrated Solar Longitude Distribution

Solar Particle Events

- Results in Increased Levels of Protons & Heavier Ions
- Energies
  - Protons - 100s of MeV
  - Heavier Ions - 100s of GeV
- Abundances Dependent on Radial Distance from Sun
- Partially Ionized - Greater Ability to Penetrate Magnetosphere Than Galactic Cosmic Rays
- Number & Intensity of Events Increases Dramatically During Solar Maximum
- Models
  - Total Ionizing Dose & Displacement Damage Dose - SOLPRO, JPL, Xapsos/NRL
  - Single Event Effects - CREME96 (Protons & Heavier Ions)

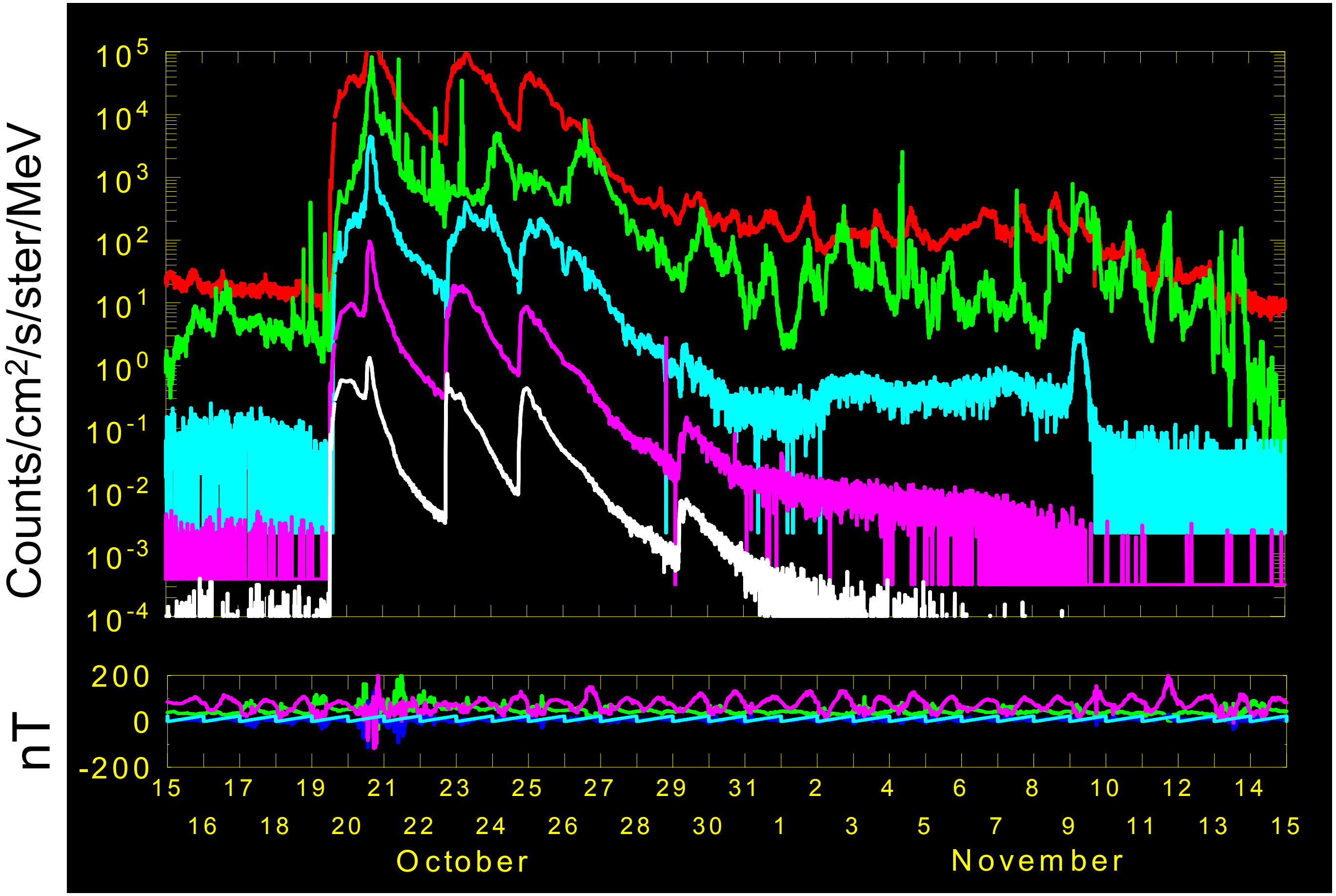
Sunspot Cycle with Solar Proton Events



Solar Proton Event - October 1989

Protons & Electrons - Magnetic Field

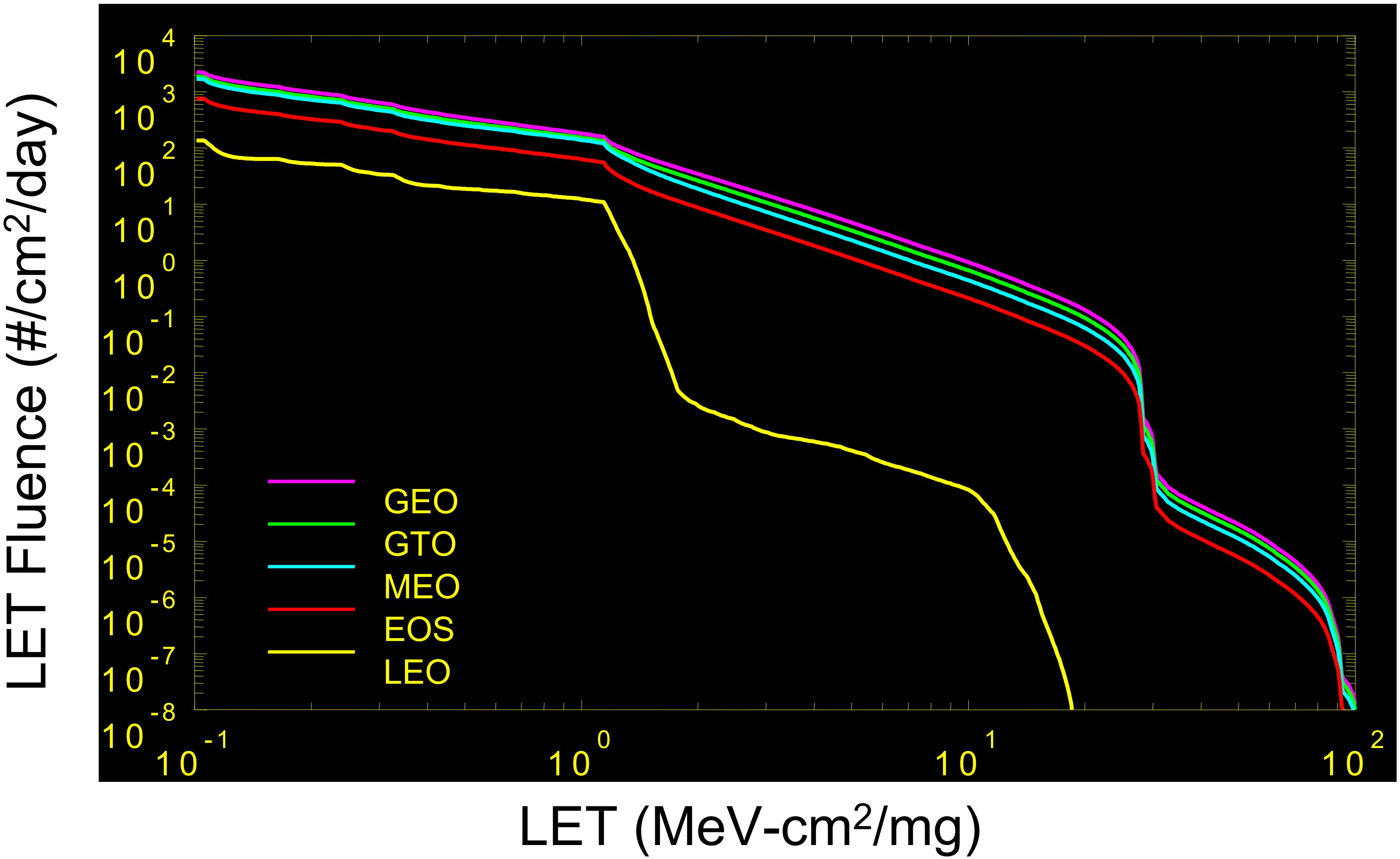
99% Worst Case Event



GOES Space Environment Monitor

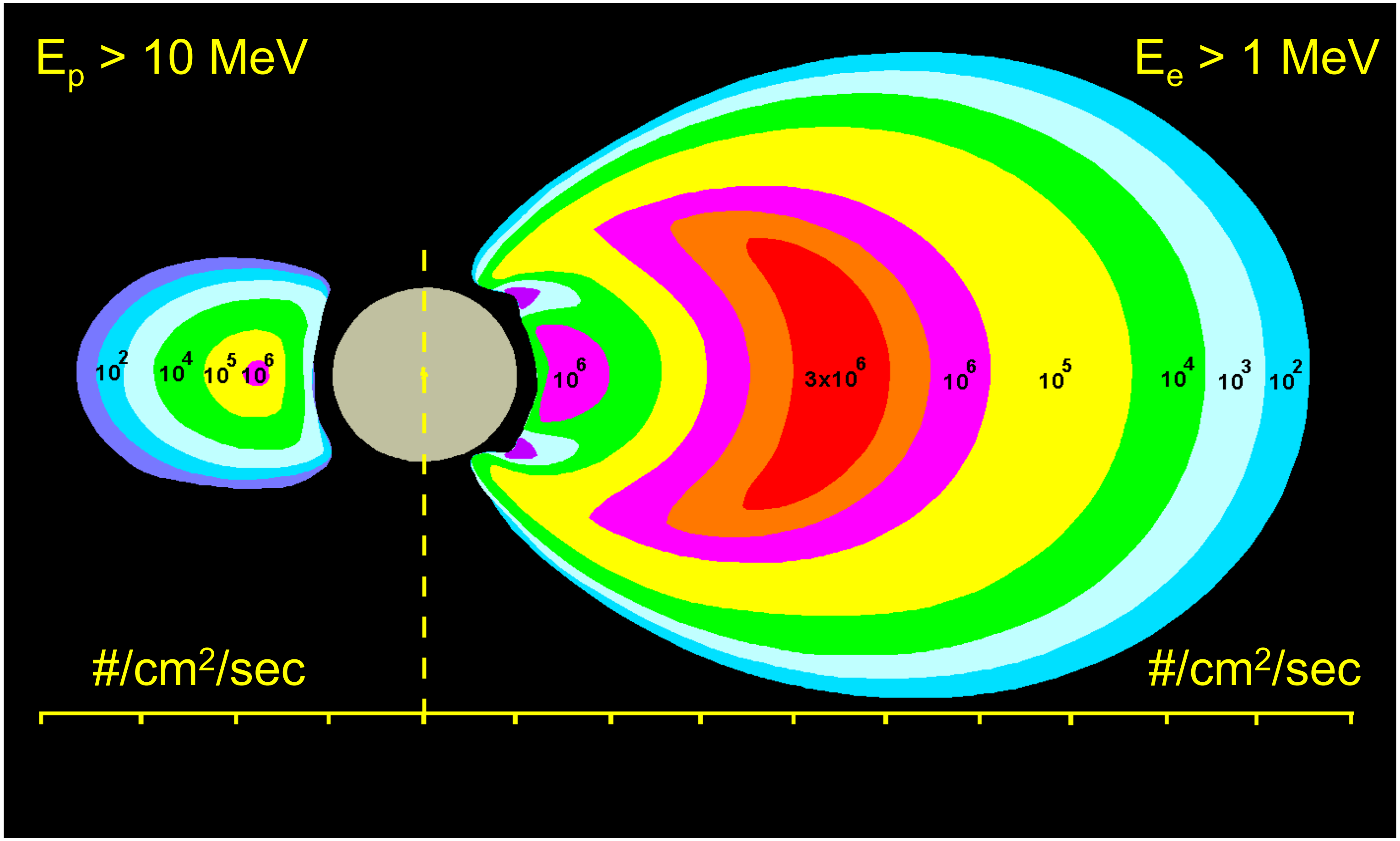
GCRs: Integral Linear Energy Transfer (LET) Spectra

CREME 96, Solar Minimum, 100 mils (2.54 mm) Al



Trapped Proton & Electron Intensities

AP-8 Model AE-8 Model

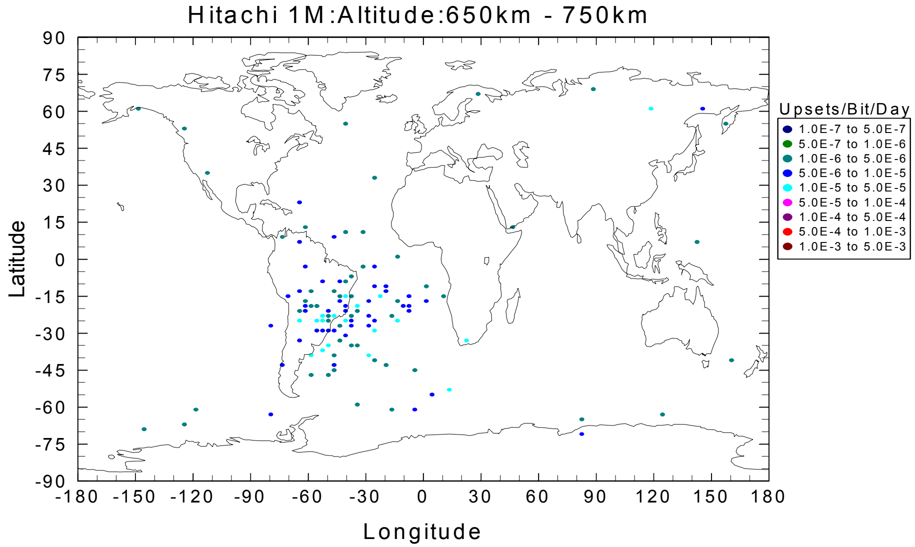


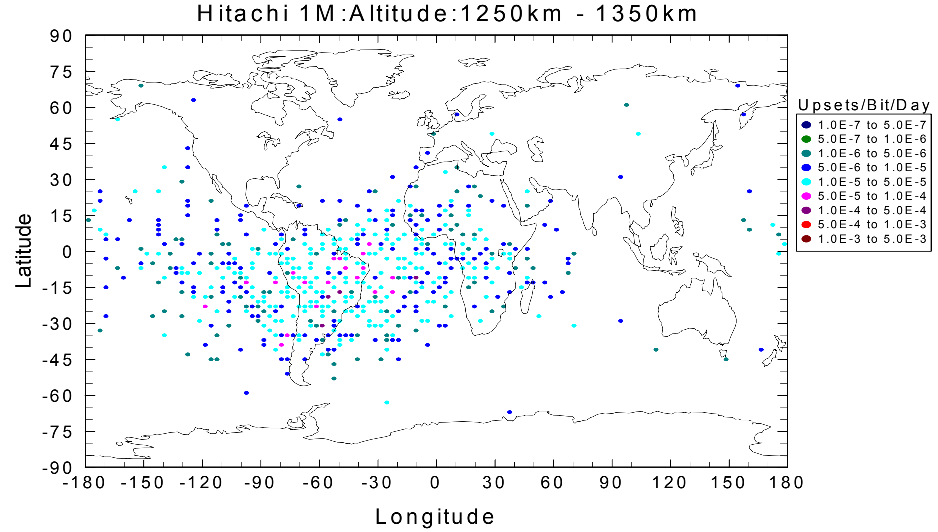
L-Shell

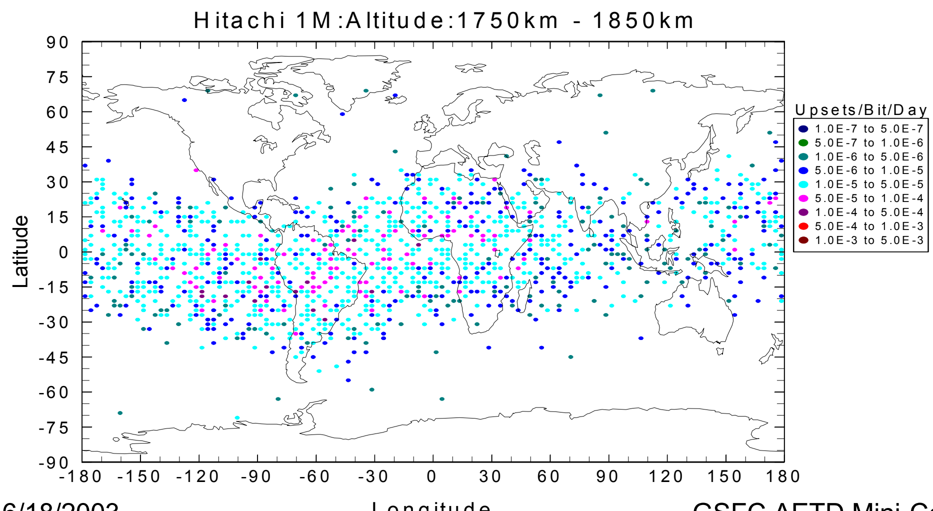
NASA/GSFC

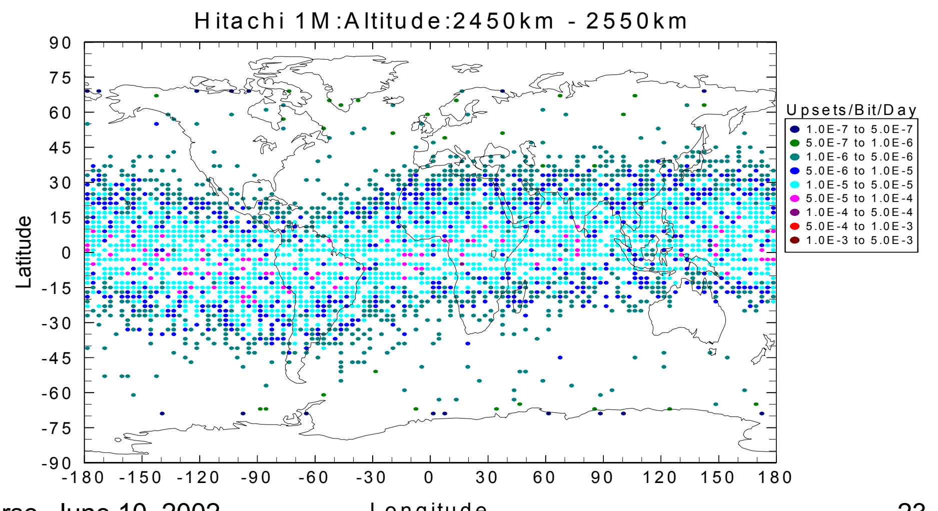
SRAM Upset Rate on CRUX/APEX

South Atlantic Anomaly (SAA) and the Proton Belt







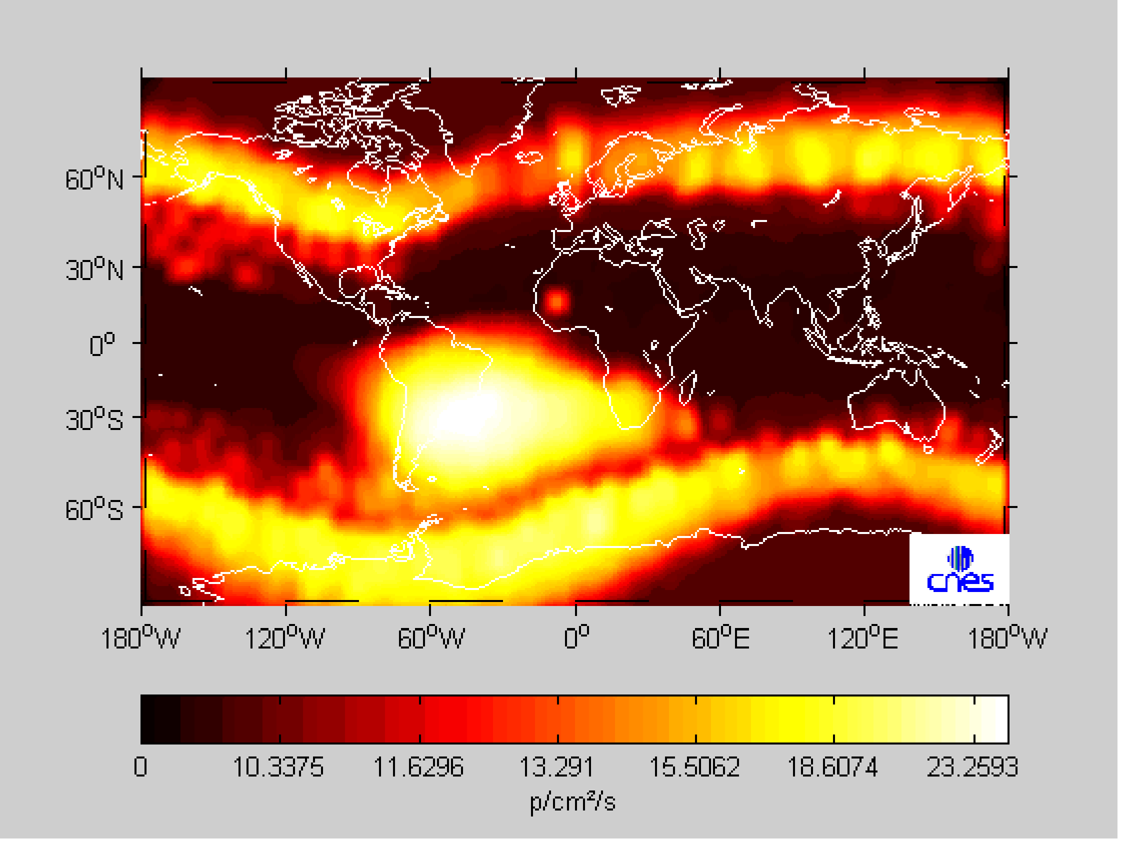


Solar Cycle Effects

- **Solar Maximum**
  - Trapped Proton Levels Lower, Electrons Higher
  - GCR Levels Lower
  - Neutron Levels in the Atmosphere Are Lower
  - Solar Events More Frequent & Greater Intensity
  - Magnetic Storms More Frequent --> Can Increase Particle Levels in Belts
- **Solar Minimum**
  - Trapped Protons Higher, Electrons Lower
  - GCR Levels Higher
  - Neutron Levels in the Atmosphere Are Higher
  - Solar Events Are Rare

Magnetic Storm and the Electron Belts

Space Weather Effect



Courtesy: R. Ecofett/CNES

Basic Radiation Effects

Radiation Effects and Spacecraft

- Critical areas for design in the natural space radiation environment
  - **Long-term effects**
    - Total ionizing dose (TID)
    - Displacement damage dose(DDD)
  - **Transient or single particle effects** (Single event effects or SEE)
    - Soft or hard errors
- Mission requirements and philosophies vary to ensure mission performance
  - What works for a shuttle mission may not apply to a deep-space mission

Total Ionizing Dose

- Cumulative long term ***ionizing*** damage due to protons & electrons
- **Effects**
  - Threshold Shifts
  - Leakage Current
  - Timing Skew
  - Functional Failures
- Can ***partially*** mitigate with shielding
  - Low energy protons
  - Electrons

Displacement Damage Dose

- Cumulative long term ***non-ionizing*** damage due to protons, electrons, and neutrons
- **Effects**
  - Production of defects which results in device degradation
  - May be similar toTID effects
  - Optocouplers, solar cells, CCDs, linear bipolar devices
- Shielding has some effect - depends on location of device
  - Can eliminate electron damage
  - Reduce some proton damage

Single Event Effects

- Event caused by a ***single charged particle***
  - Heavy ions
  - Protons for sensitive devices
- **Effects**
  - Non-destructive: SEU, SET, MBU, SEBE, SHE
  - Destructive: SEL, SEGR, SEB
- Severity is dependent on
  - type of effect
  - system criticality
- Shielding has **little** effect

Radiation Effects: The Root Cause in the Natural Radiation Environments

- **Total Ionizing Dose**
  - Trapped Protons & Electrons
  - Solar Protons
- **Single Event Effects**
  - Protons
    - Trapped
    - Solar
  - Heavier Ions
    - Galactic Cosmic Rays
    - Solar Events
  - Neutrons
- **Displacement Damage**
  - Protons
  - Electrons
- **Spacecraft Charging**
  - Surface
    - Plasma
  - Deep Dielectric
    - High Energy Electrons
- Background Interference on Instruments

NASA and Radiation Requirements

NASA and Radiation Requirements

- NASA deals with the natural space (or atmospheric) radiation environment only
- Radiation effects on NASA technology are limited to:
  - Total ionizing dose (TID)
  - Displacement Damage Dose (DDD)
  - Single Event Effect (SEE)
- Induced radiation environments are not a direct concern to NASA
  - Note: induced secondaries are of concern
- The following chart illustrates relative NASA requirements versus mission types
  - ***Note: TID levels noted assume a nominal amount of effective shielding***

Radiation Device Regimes for the Natural Space Environment

- High
  - > 100 krads (Si)
  - May have
    - long mission duration
    - intense single event environment
    - intense displacement damage environment
- Moderate
  - 10-100 krads (Si)
  - May have
    - medium mission duration
    - intense single event environment
    - moderate displacement damage environment
- Low
  - < 10 krads (Si)
  - May have
    - short mission duration
    - moderate single event environment
    - low displacement damage environment

Examples: Europa, GTO, MEO Type of device: Rad hard (RH)	Examples: EOS, highLEO, L1, L2, ISSA Type of device needed: Rad tolerant (RT)	Examples: HST, Shuttle, XTE Type of device needed: SOTA commercial with SEE mitigation

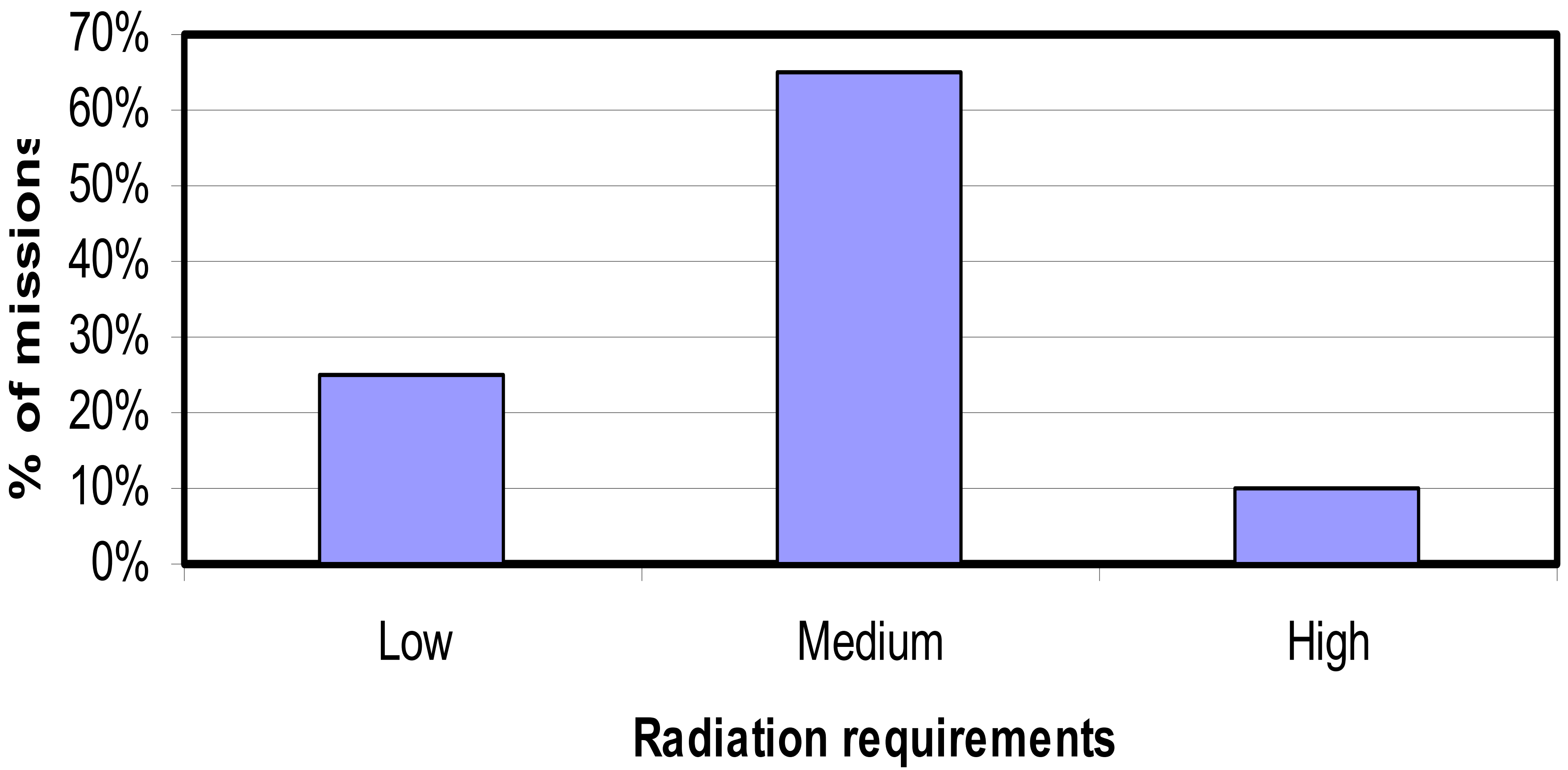
Aeronautics must deal with neutron SEE environment

NASA Missions

- Approximately 225 missions are currently in some stage of development
  - Some are large (ex., International Space Station (ISS))
  - Some are small (ex. ST-5 nanosats, part of the New Millenium Program)
  - Many are in the middle (ex,, MIDEX - medium class explorers)
- All are trying to conserve resources
  - Programmatic: funds, manpower, schedule, etc.
  - Technical: power, weight, volume, etc.

Mix of NASA Missions and Radiation Requirements

- Informal study has been performed of percent of missions in each category



Implications of NASA Mission Mix

- ***SEE tolerant is the major current need***
- "Radiation Tolerant" covers a large percentage of NASA needs
- "Commercial" (non-hardened) devices or even boards and systems may be acceptable for some NASA missions (with the risks associated with commercial devices)
  - Even the low radiation requirement offers challenges for commercial devices
    - Example: Hubble Space Telescope has noted numerous anomalies on commercial microelectronics
- Projects with rad hard needs struggle to meet requirements
  - Limited device availability or implications of adding mitigation
- An increase in available rad hard technologies opens the door for mission options that are desirable but not currently thought to be feasible
  - Ex., Enables routine operation and science in MEO and Deep Space
- Two Further Notes:
  - Aero-Space (avionics/terrestrial) has issues with soft errors (typically induced by secondary neutrons)
  - NASA designs use all types of microelectronics from true rad-hard to Radio Shack COTS (Ex., shuttle experiment)

Next Generation Space Telescope: Electronics Drivers

- Radiation hazards (L2, launch 2010)
  - GCR, solar particle events, trapped electrons
- Radiation requirements
  - Mostly radiation tolerant needs, however…
- Non-radiation drivers
  - Instrument requirements (IR detectors)
    - Ultra-low noise (better than the state-of-the-art)
    - Cold temperature
    - Mirrors, Deployable Structures, Optical Fiber
- Philosophy
  - Analysis underway; Testing expected

International Space Station: Electronics Drivers

- Radiation hazards (low earth, 57 deg inclination)
  - Primarily trapped protons, some GCR and solar particles
- Radiation requirements
  - High amounts of effective shielding
  - Proton upset is prime driver; GCR is secondary
- Non-radiation drivers
  - Large amounts of hardware
  - Serviceable
- Philosophy
  - Use off COTS and COTS boards
  - Use proton ground tests to qualify hardware ***(controversial)***

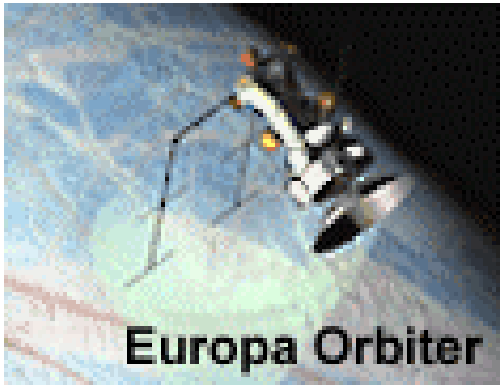
Ziatech ZT-6500 3U Compact PCI Pentium Board.

Space Shuttle: Electronics Drivers

- Radiation hazards (Mostly ISS orbits)
  - Trapped particles, some GCR and solar particles
- Radiation requirements
  - Shuttle upgrades require radiation tolerant
  - Experiments have none other than fail-safe
- Non-radiation drivers
  - Serviceable
  - Short duration
  - Performance not a driver
- Philosophy
  - Radio Shack for experiments

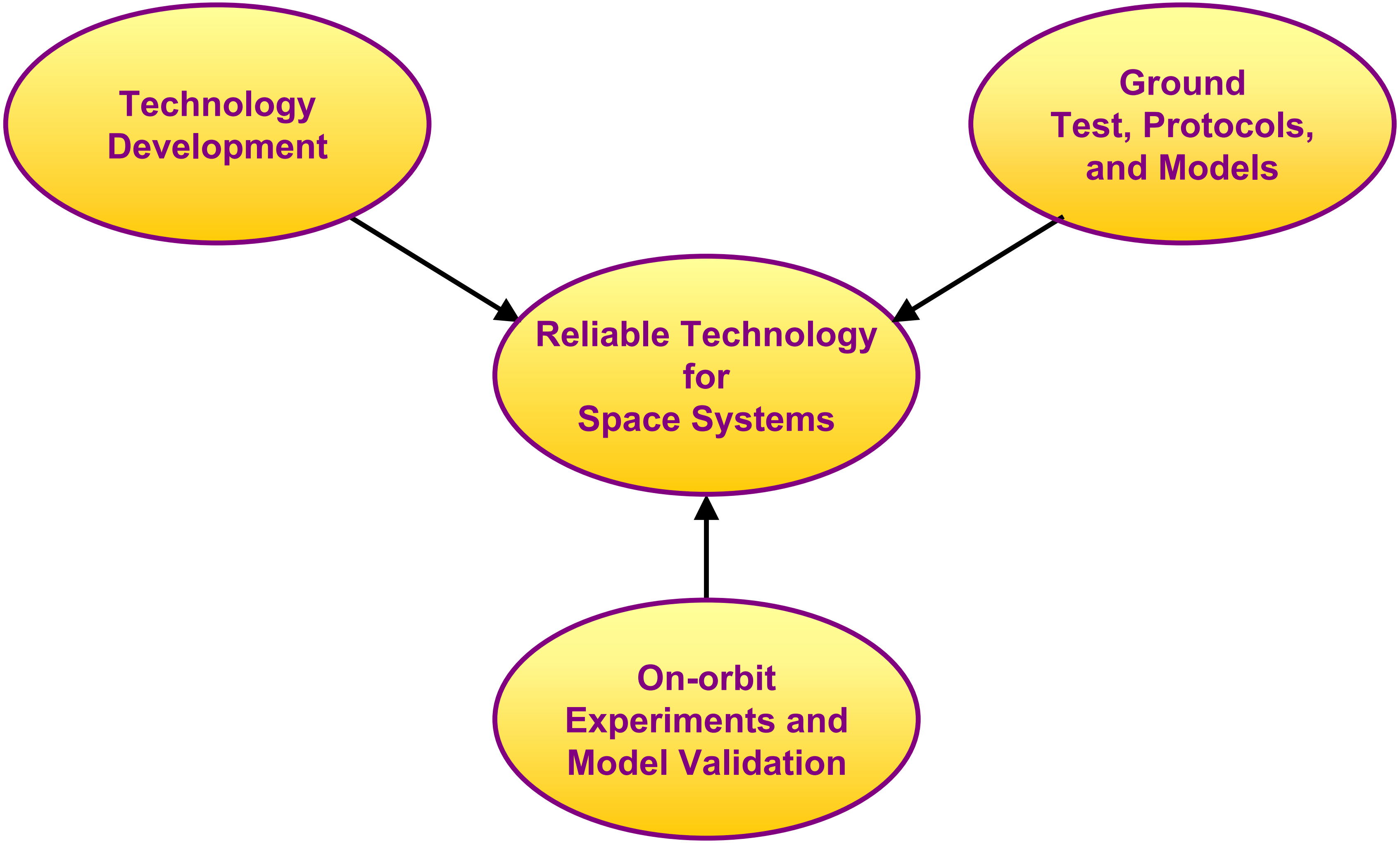
Europa: Electronics Drivers

- Radiation hazards (Jovian Deep Space)
  - Trapped particles (electrons!), GCR, solar particles
- Radiation requirements
  - High
- Non-radiation drivers
  - 7 year storage of many instruments and systems
  - Temperature range
- Philosophy
  - Rad hard where they can
    - Custom Rad hard ASICs
  - Mitigation/shielding where they can't



Radiation and Technology

Technology Triumvirate for Insertion Into Spaceflight



NASA Technology Programs

- **Technology Development**
  - Cross Enterprise Technology Development Program (CETDP)
  - Individual NASA Enterprises
  - Individual Flight Programs/Projects
- **Technology Ground Evaluation**
  - Electronic Radiation Characterization Project (ERC) (a portion of the NASA Electronic Parts and Packaging (NEPP) Program)
  - Individual Flight Programs/Projects
- **Flight Validation**
  - New Millennium Program
    - Emphasizes system and sub-system level validation
  - **Living With a Star/Space Environment Testbed (SET)**
    - Emphasizes technologies that are affected by solar variability (re: ionizing radiation)
    - Develops prediction models, tool, and guidelines

Desirable Features for Future NASA Missions - Factors Affecting Microelectronics

- Higher functional integration/density
  - System-on-a-chip
- Modular system design
- Advanced packaging techniques
- Low and ultra-low power
- Fault tolerant
- Reconfigurable systems
- Rapid prototyping/simulation
- Scalable real-time multiprocessing
- Operation at hot/cold temperature
- High-bandwidth (communications, free space interconnects, etc.)
- Increased processing capability
  - On-board autonomy, data reduction
- Integrated power management and distribution
- Increased reliability
- Increased availability, reduced cost, …
- **Radiation tolerance**

NASA Needs for Microelectronics Technology

- In general, NASA is tasked to
  - reduce time-to-launch (faster)
  - increase system performance (better), and
  - reduce spacecraft and instrument size and power as well as ground-based manpower (cheaper).
- This implies that NASA microelectronics require
  - increased technical performance (bandwidth, power consumption, volume, etc.), and
  - increased programmatic performance (availability, cost, reliability).
- ***Radiation tolerance is the "red-headed stepchild" of this process.***
  - Current programs often "waive" or reduce reliability/radiation tolerance issues or design workarounds
- "True" cost of commercial versus radiation hardened is often misunderstood

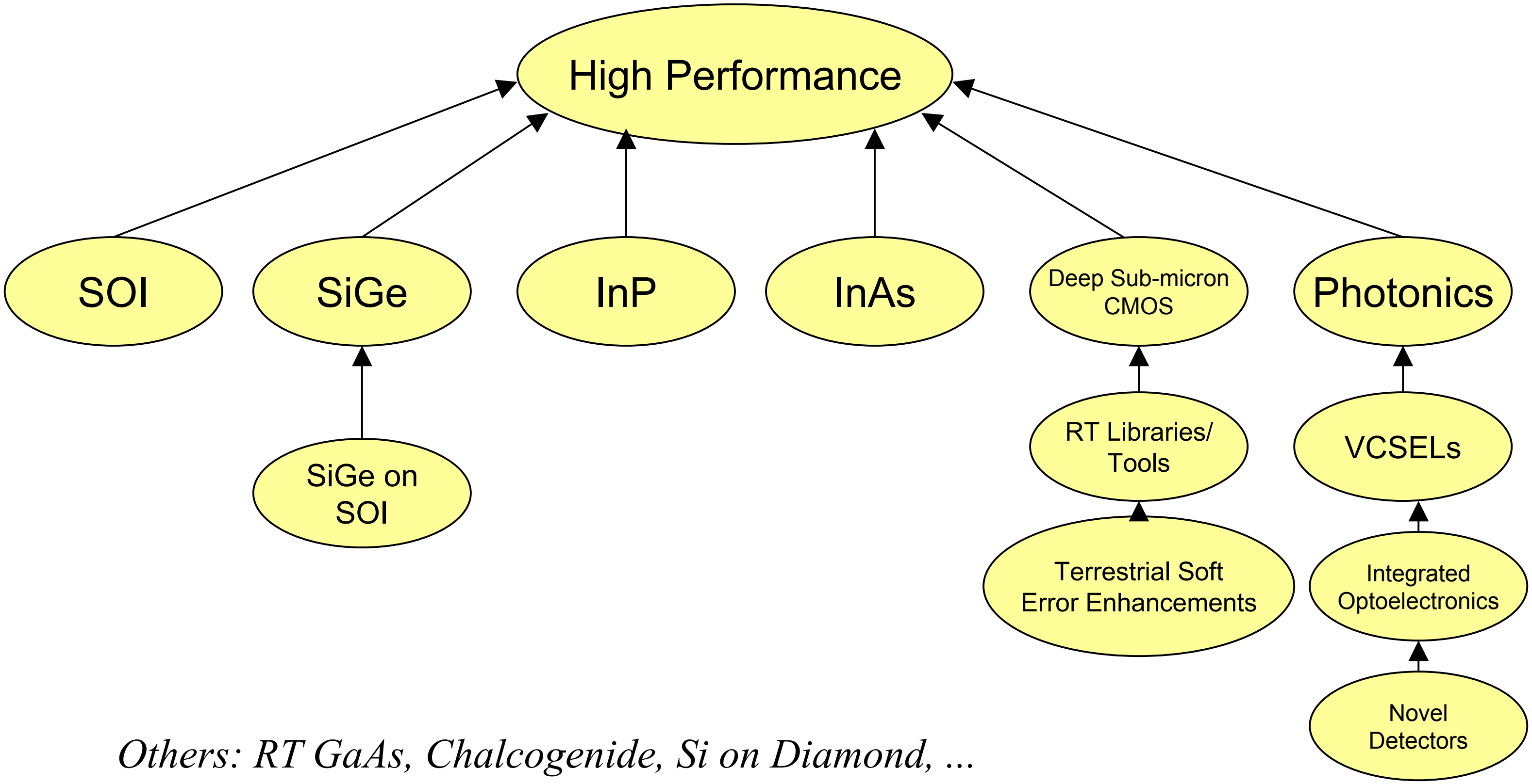
Sample Cost Factors for Selecting Commercial Versus Rad Hard Device

- Procurement
- Screening
- Radiation Testing
- Availability
- Development Tools
- Prototypes
- Manpower
- Shielding
- Circuit Mitigation
- Development Path

- Technical (re: need for Mflops) may be the driver over cost

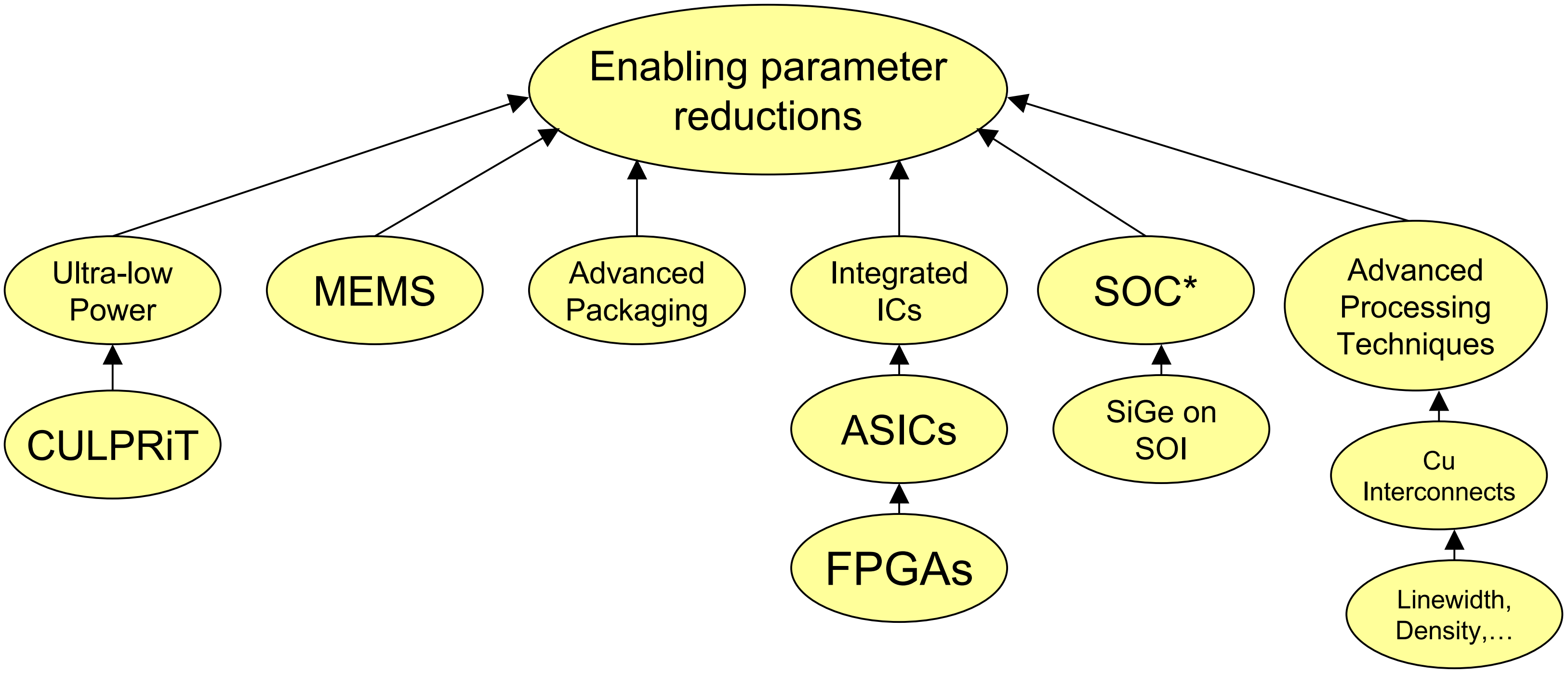
*- Other factor to consider: **risk***

Microelectronics Technologies for NASA Roadmap - Breakthrough Bandwidth/Speed



Others: RT GaAs, Chalcogenide, Si on Diamond, ...

Microelectronics Technologies for NASA Roadmap - Breakthrough Volume



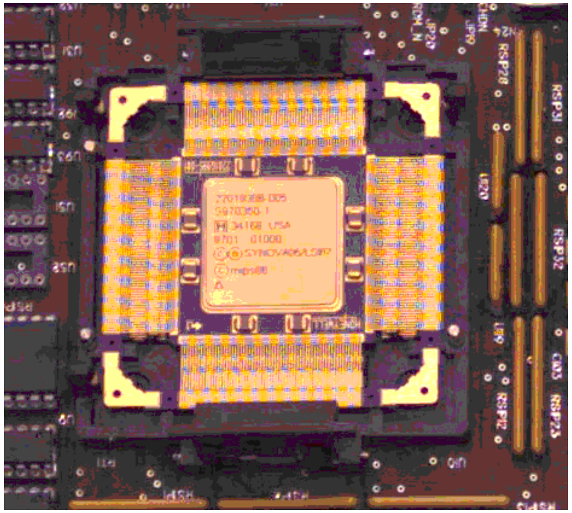
** = system-on-a-chip: may include numerous technologies including mixed signals (analog/digital) on single substrate*

Radiation Issues for Newer Technologies

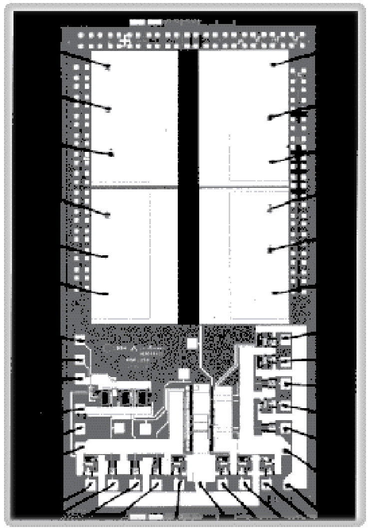
- Proton induced single event upsets
- Proton induced single event latchup
- Neutron & Alpha induced upsets
- Single events in Dynamic RAMs
- Displacement damage in electronics
- Single event functional interrupt
- Stuck bits
- Block errors in Dynamic RAMs
- **Single event transients**
- Neutron induced single event effects
- Hard failures & latchup conditions
- Multiple upsets from a single particle
- Feature size versus particle track
- Microdose
- **Enhanced low dose rate sensitivity (ELDRS)**
- Reduced shielding
- Test methods for advanced packaged devices
- **Ultra-high speed & novel devices (e.g., photonics, InP, SiGe)**
- Design margins & mitigation
- **COTS variability**
- At-speed testing
- Application-specific sensitivities

In general, however, TID tolerance of deep submicron CMOS is improving

Silicon on Insulator (SOI) Technology



Mongoose V
http://www.synova.com/proc/mg5.html



ASP1150 1/2 AMP SOLENOID DRIVER
http://www.mtcsemi.com/html/asp1150.html

Prime Driver:

- Hand-held products that require:
  - High levels of integration, and
  - very low power consumption

Advantages:

- Reduced power consumption
- Low noise
- Performance improvements

May:

- Provide commercial solution to soft error sensitivity at reduced power supply voltages

Applications:

- Digital, analog, mixed signal

Sample devices:

- Mongoose V processor
- 256 kbit SRAM
  - 1.2V operation comparable to >2V bulk device

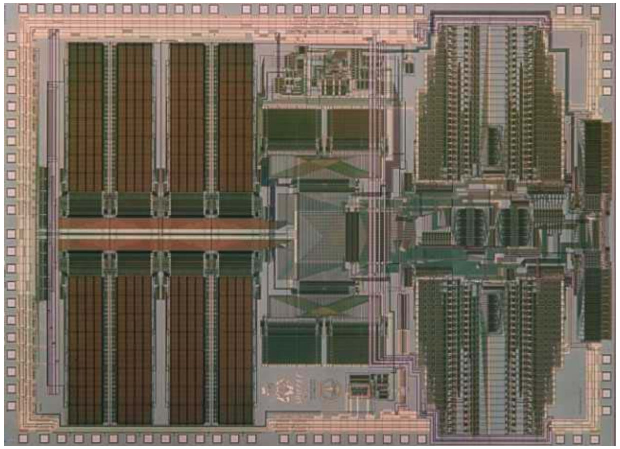
Radiation Issues:

- Different between commercial and rad hard
- More robust to SEE than bulk CMOS
- TID varies

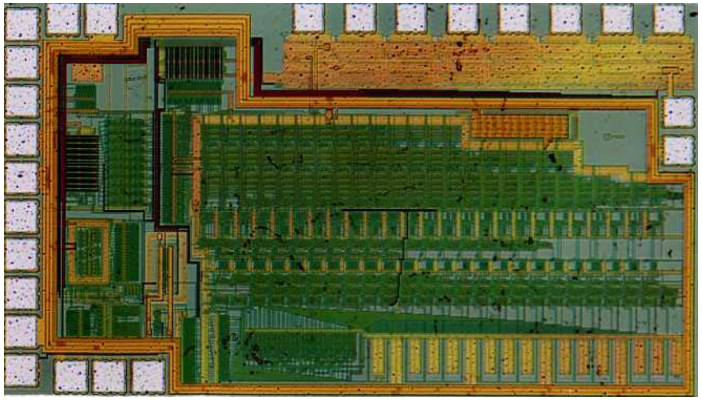
Comment:

- Issues of yield/production

Ultra-Low Power (ULP) Technology Microelectronics



1024-point
FFT processor



20bit x 20bit
Pipelined Multiplier

Prime Driver:

Hand-held products that require:

- High levels of integration, and
- very low power consumption

Advantages:

- Reduced power consumption with VCC <1V
- Allows for enabling volume shrinkage for space application

May:

- Provide true "nanosat" technology

Applications:

- Mostly digital at this time

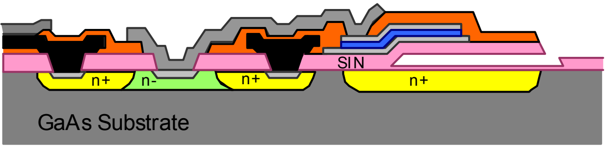
Radiation Issues:

- Upset sensitivity
  - Rad-tolerant effort (CULPRiT) at UNM

Comment:

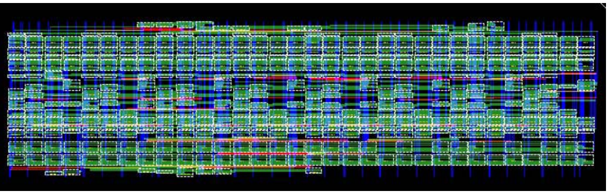
- Other reliability issue such as ultra-thin silicon dioxide gate dielectrics
- Electromigration issues with minimum pitch interconnect

GaAs Semiconductors



Representative cross section of a GaAs-based microbeam accelerometer. The approach combines piezoelectric thin films with micromachined structures on a GaAs substrate with MESFET electronics.

http://www.topvu.com/html/technical_information.html



32 Bit CGaAs Adder
http://www-personal.engin.umich.edu/~phiroze/32bitAdder.html

Driver:

Cellular telephones and wireless communications

Advantages:

High operational speed and linearity
Ability to operate at reduced power supply voltages

Current trends:

Higher integration
Reduced substrate costs

May:

Be ideal for multi-frequency (re: dual-band) phones

Applications:

Analog, digital, or mixed signal

Radiation Issues:

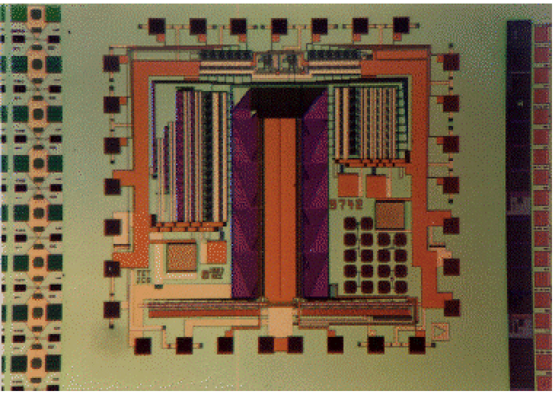
SEU sensitivity

Comments:

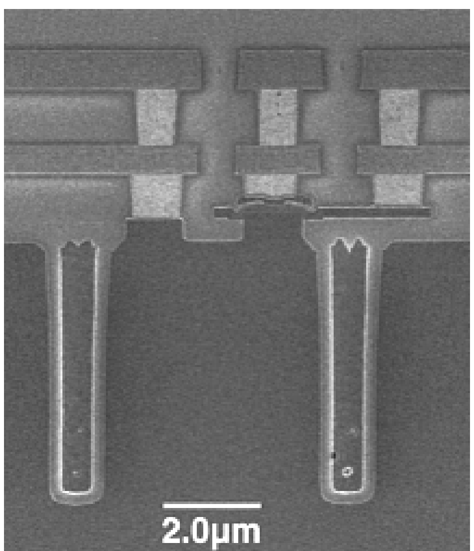
Emergence of Complementary GaAs (CGaAs) or other more SEU-tolerant technologies (LT buffers)

- increased density and reduced power consumption traded with operating speed (<1GHz)

SiGe Semiconductors



SiGe IC



SiGe SEM
Cross-Section

Driver:

Handheld products

Advantages:

Higher Speed than Si (>75 GHz possible)
Compatible with existing Si technology
Low noise floor and high power gain imply mixed-signal (cellular phone-on-a-chip) potential
May be “tuned” by selective doping

May:

Compete with III-V semiconductors

Applications:

Digital, analog, mixed signal (cellular phone-on-a-chip)

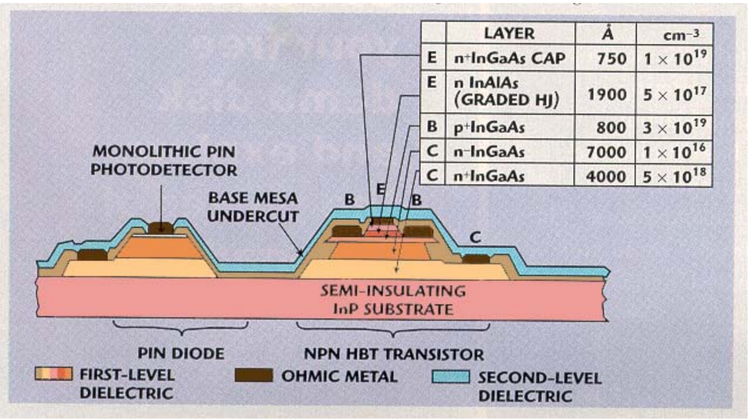
Sample Device:

12-bit DAC with 1.2 Gbps operation
- outperforms comparable bipolar devices

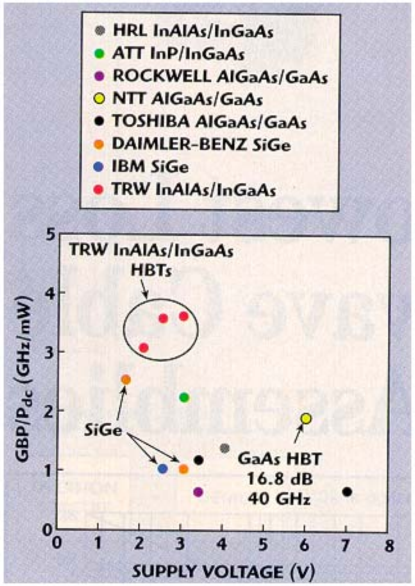
Radiation Issues:

Preliminary TID and displacement damage results look promising
SEU sensitivity demonstrated

InP Semiconductors



A cross section of the InAlAs/InGaAs HBT Device.



A comparison of InP HBT direct-coupled amplifiers.

Driver:

Mobile communications

Advantages:

Ultra-high Speed (>100 GHz)
Low phase noise
Excellent thermal conductivity
Compatibility with Si

May:

Provide an “ideal” space solution

Applications:

Digital, mixed signal primarily

Radiation Issues :

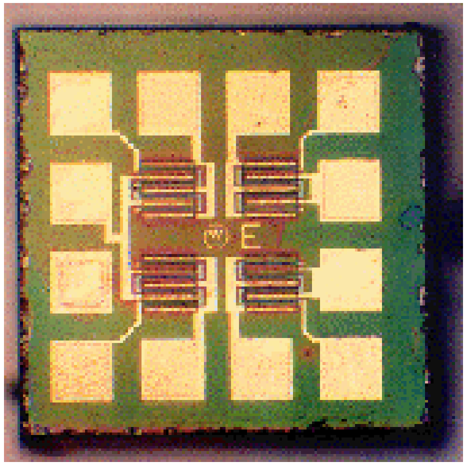
Preliminary results promising,
but mostly proprietary

Comments:

Still in prototype stage
Material quality and availability

Wide Bandgap (WBG) Semiconductors

GaN Bulk Crystal Growth



SiC IC

Sample Technologies:

SiC, GaN, Diamond, and AIN

Advantages:

High temperature and power density levels
High thermal conductance
High electron carrier velocities

May:

Replace some Si-based or high-frequency Vacuum tube technologies while reducing weight, power, and complexity

Applications:

MMICs for phased array radar power amplifier,
cross-and down-link power amplifiers,
power conversion products
novel packaging

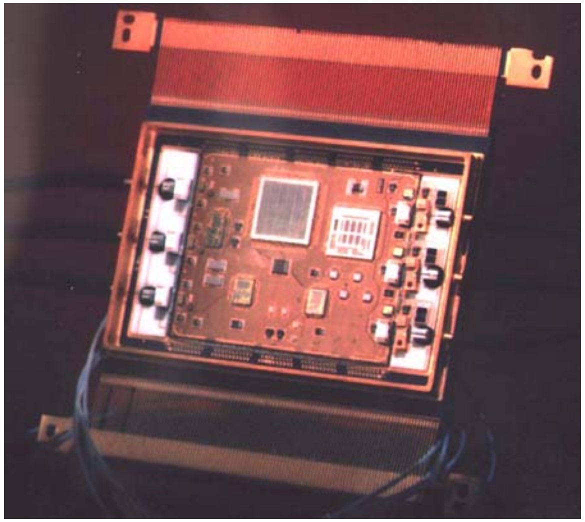
Radiation Issues:

Open

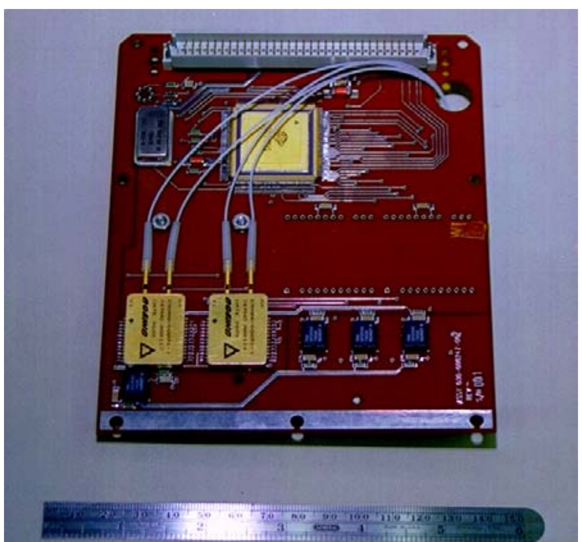
Comment:

Materials fabrication issues
Material quality and availability

Fiber Optic System Applications



FODB CFBIU MCM



Microelectronics and Photonics Test Bed

Prime Driver:

Terrestrial telephone and communication links

Advantages:

Reduced volume, weight
Increased performance (>1Gbps)
Reduced EMI/EMC
Architectural scalability

May:

Replace existing command and data interfaces

Applications:

Data and command transfer

Sample Developments:

PFODB, SFODB, commercial:FC, ethernet ...

Radiation Issues:

Design dependent
Associated electronics are often the radiation driver
Hardening approaches possible

Comment:

Many new technologies emerging
Several systems currently in space
Higher (ie: >1Gbps) rate systems sought
(image processing, optical processing, …)

System Level Approach to Radiation Hardness Assurance (RHA)

Sensible Programmatics for Radiation Hardness Assurance (RHA):
A Two-Pronged Approach

- Assign a **lead radiation engineer** to each spaceflight project
  - Treat radiation like other engineering disciplines
    - Parts, thermal,...
  - Provides a single point of contact for all radiation issues
    - Environment, parts evaluation, testing,…
- Each program follows a **systematic approach to RHA**
  - RHA active early in program reduces cost in the long run
    - Issues discovered late in programs can be expensive and stressful
      - What is the cost of reworking a flight board if a device has RHA issues?

Radiation and Systems Engineering: A Rational Approach for Space Systems

- Define the Environment
  - External to the spacecraft
- Evaluate the Environment
  - Internal to the spacecraft
- Define the Requirements
  - Define criticality factors
- Evaluate Design/Components
  - Existing data/Testing/Performance characteristics
- "Engineer" with Designers
  - Parts replacement/Mitigation schemes
- Iterate Process
  - Review parts list based on updated knowledge

Define the Hazard

- The radiation environment **external** to the spacecraft
  - Trapped particles
    - Protons
    - Electrons
  - Galactic cosmic rays (heavy ions)
  - Solar particles (protons and heavy ions)
- Based on
  - Time of launch and mission duration
  - Orbital parameters, …
- Provides
  - Nominal and worst-case trapped particle fluxes
  - Peak “operate-through” fluxes (solar or trapped)
  - Dose-depth curve of total ionizing dose (TID)

We are currently using static models for a dynamic environment

Evaluate the Hazard

- Utilize mission-specific geometry to determine particle fluxes and TID at locations **inside** the spacecraft
  – 3-D ray trace (geometric sectoring)
- Typically multiple steps
  – Basic geometry (empty boxes,…) or single electronics box
  – Detailed geometry
    - Include printed circuit boards (PCBs), cables, integrated circuits (ICs), thermal louvers, etc…
- Usually an iterative process
  – Initial spacecraft design
  – As spacecraft design changes
  – Mitigation by changing box location

Define Requirements

- Environment usually based on hazard definition with “nominal shielding” or basic geometry
  - Using actual spacecraft geometry sometimes provides a “less harsh” radiation requirement
- Performance requirements for “nominal shielding” such as 70 mils of Al or actual spacecraft configuration
  - TID
  - DDD (protons, neutrons)
  - SEE
    - Specification is more complex
    - Often requires SEE criticality analysis (SEECA) method be invoked
- **Must** include radiation design margin (RDM)
  - At least a factor of 2
  - Often required to be higher due to device issues and environment uncertainties

System Requirements - SEE Specifications

- For TID, parts can be given A number (with margin)
  - SEE is much more application specific
- SEE is unlike TID
  - Probabilistic events, not long-term
    - Equal probabilities for 1st day of mission or last day of mission (maybe by definition!)

SEE - System Requirements (1 of 2)

- SEE (1 of 2)
  - based on predicted environment and criticality of function performed*
  - 3 categories of **criticality**:
    - Error-critical: SEEs are unacceptable
    - Error-vulnerable: A low risk of SEE is acceptable
    - Error-functional: SEEs are acceptable. Mitigation means may be added to make these SEEs acceptable.
  - Examples: pyro controller would be *error-critical*; a solid state recorder (SSR) would be SEU *error-functional*.

* *For further information see: Single Event Effects Criticality Analysis (SEECA) at* ***http://radhome.gsfc.nasa.gov/radhome/papers/seecai.htm***

SEE - System Requirements (2 of 2)

- SEE (2 of 2)
  - No SEE may cause permanent damage to a system or subsystem
  - 3 Areas of device categories to evaluate based on Linear Energy Transfer (LET) threshold (LETth) criteria. LETth is the maximum LET value at which no SEE is observed.
    - LETth > 100 MeV*cm2/mg. No analysis required.
    - LETth between 10-100 MeV*cm2/mg. Analysis performed for heavy ion component.
    - LETth < 10 MeV*cm2/mg. Analysis performed for heavy ion and proton components.
  - ***Analysis (SEE rate prediction) must be performed not only for nominal conditions, but worst-case operate-through conditions*****.**

Single Event Effects Specification (1 of 3)

1. Definitions and Terms

Single Event Upset (SEU) - a change of state or transient induced by an energetic particle such as a cosmic ray or proton in a device. This may occur in digital, analog, and optical components or may have effects in surrounding interface circuitry (a subset known as Single Event Transients (SETs)). These are “soft” errors in that a reset or rewriting of the device causes normal device behavior thereafter.

Single Hard Error (SHE) - an SEU which causes a permanent change to the operation of a device. An example is a stuck bit in a memory device.

Single Event Latchup (SEL) - a condition which causes loss of device functionality due to a single event induced high current state. An SEL may or may not cause permanent device damage, but requires power strobing of the device to resume normal device operations.

Single Event Burnout (SEB) - a condition which can cause device destruction due to a high current state in a power transistor.

Single Event Gate Rupture (SEGR) - a single ion induced condition in power MOSFETs which may result in the formation of a conducting path in the gate oxide.
Single Event Effect (SEE) - any measurable effect to a circuit due to an ion strike. This includes (but is not limited to) SEUs, SHEs, SELs, SEBs, SEGRs, and Single Event Dielectric Rupture (SEDR).

Multiple Bit Upset (MBU) - an event induced by a single energetic particle such as a cosmic ray or proton that causes multiple upsets or transients during its path through a device or system.

Linear Energy Transfer (LET) - a measure of the energy deposited per unit length as a energetic particle travels through a material. The common LET unit is MeV*cm^2/mg of material (Si for MOS devices, etc.).
Threshold LET (LET_{th}) - the minimum LET to cause an effect at a particle fluence of 1E7 ions/cm^2. Typically, a particle fluence of 1E5 ions/cm^2 is used for SEB and SEGR testing.

Single Event Effects Specification (2 of 3)

2. Component SEU Specification

2.1 No SEE may cause permanent damage to a system or subsystem.

2.2 Electronic components shall be designed to be immune to SEE induced performance anomalies, or outages which require ground intervention to correct. Electronic component reliability shall be met in the SEU environment.

2.3 If a device is not immune to SEUs, analysis for SEU rates and effects must take place based on LET_{th} of the candidate devices as follows:

Device Threshold	Environment to be Assessed
LET_{th} < 10 MeV*cm^2/mg	Cosmic Ray, Trapped Protons, Solar Proton Events
LET_{th} = 10-100 MeV*cm^2/mg	Galactic Cosmic Ray Heavy Ions, Solar Heavy Ions
LET_{th} > 100 MeV*cm^2/mg	No analysis required

2.4 The cosmic ray induced LET spectrum which shall be used for analysis is given in Figure TBD.

2.5 The trapped proton environment to be used for analysis is given in Figures TBD. Both nominal and peak particle flux rates must be analyzed.

2.6 The solar event environment to be used for analysis is given in Figure TBD.

2.7 For any device that is not immune to SEL or other potentially destructive conditions, protective circuitry must be added to eliminate the possibility of damage and verified by analysis or test.

Single Event Effects Specification (3 of 3)

2. Component SEU Specification (Cont.)

2.8 For SEU, the *criticality* of a device in it's specific application must be defined into one of three categories: error-critical, error-functional, or error-vulnerable. Please refer to the /radhome/papers/seecai.htm Single Event Effect Criticality Analysis (SEECA) document for details. A SEECA analysis should be performed at the system level.

2.9 The improper operation caused by an SEU shall be reduced to acceptable levels. Systems engineering analysis of circuit design, operating modes, duty cycle, device criticality etc. shall be used to determine acceptable levels for that device. Means of gaining acceptable levels include part selection, error detection and correction schemes, redundancy and voting methods, error tolerant coding, or acceptance of errors in non-critical areas.

2.10 A design's resistance to SEE for the specified radiation environment must be demonstrated.

3. SEU Guidelines

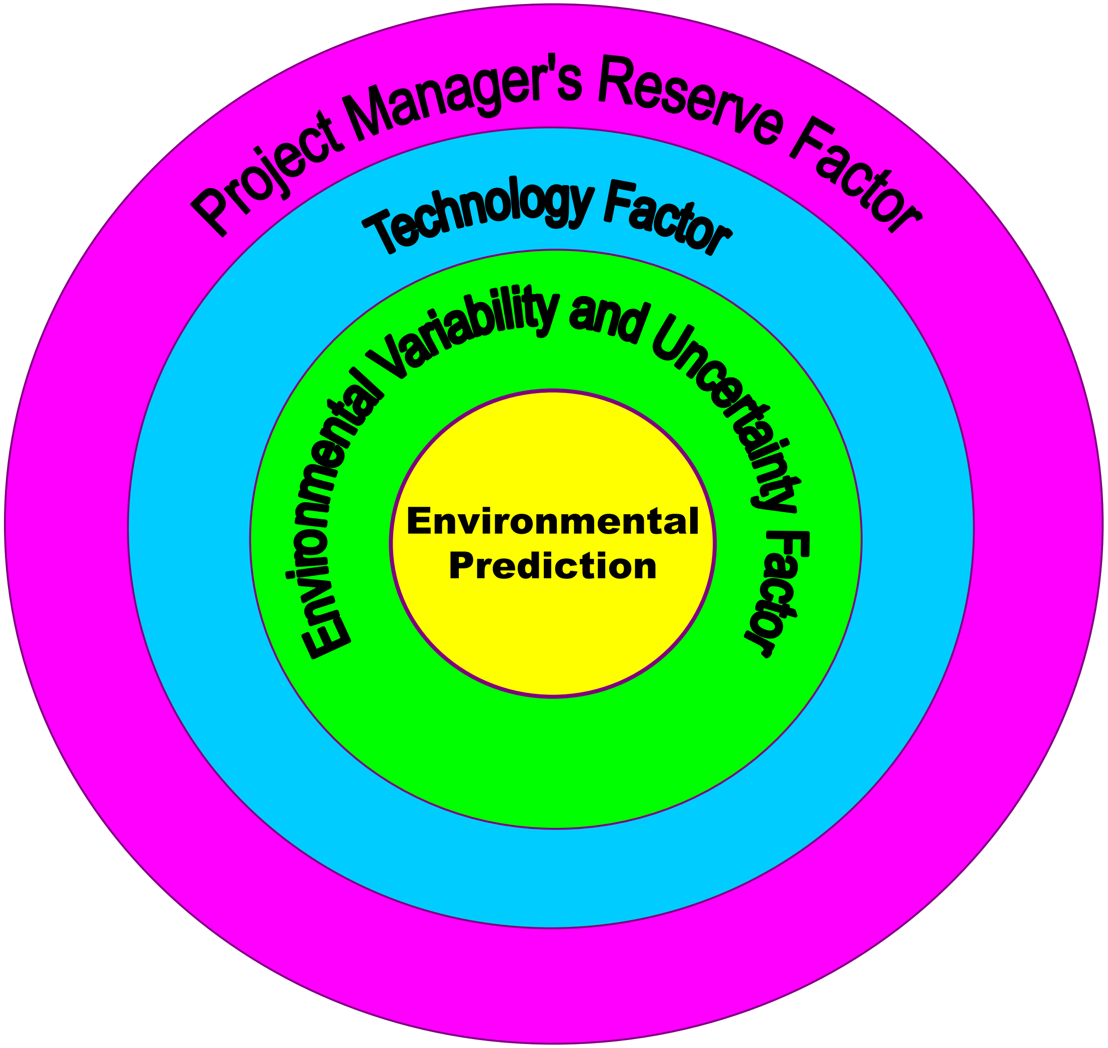
Wherever practical, procure SEE immune devices. SEE immune is defined as a device having an LET_{th} > 100 MeV*cm^2/mg.

If device test data does not exist, ground testing is required. For commercial components, testing is recommended on the flight procurement lot.

Notes on System Requirements

- Requirements do NOT have to be for piecepart reliability
  - For example, may be viewed as a “data loss” specification
    - Acceptable bit error rates or system outage
  - Mitigation and risk are system trade parameters
  - Environment needs to be defined for **YOUR** mission (can’t use prediction for different timeframe, orbit, etc…)

The RDM Process



Radiation Design Margins (RDMs) - 1 of 2

- How much risk does the project want to take?
- Uncertainties that must be considered
  - Dynamics of the environment
  - Test data
    - Applicability of test data
      - Does the test data reflect how the device is used in THIS design?
    - Device variances
      - Lot-to-lot, wafer-to-wafer, device-to-device

Radiation Design Margins (RDMs) - 2 of 2

- Is factor of 2 enough?
  - For some issues such as ELDRs, no.
- Is factor of 5 too high?
  - It depends
- Risk trade
  - Weigh RDM vs. cost/performance vs. probability of issue vs. system reliability etc…

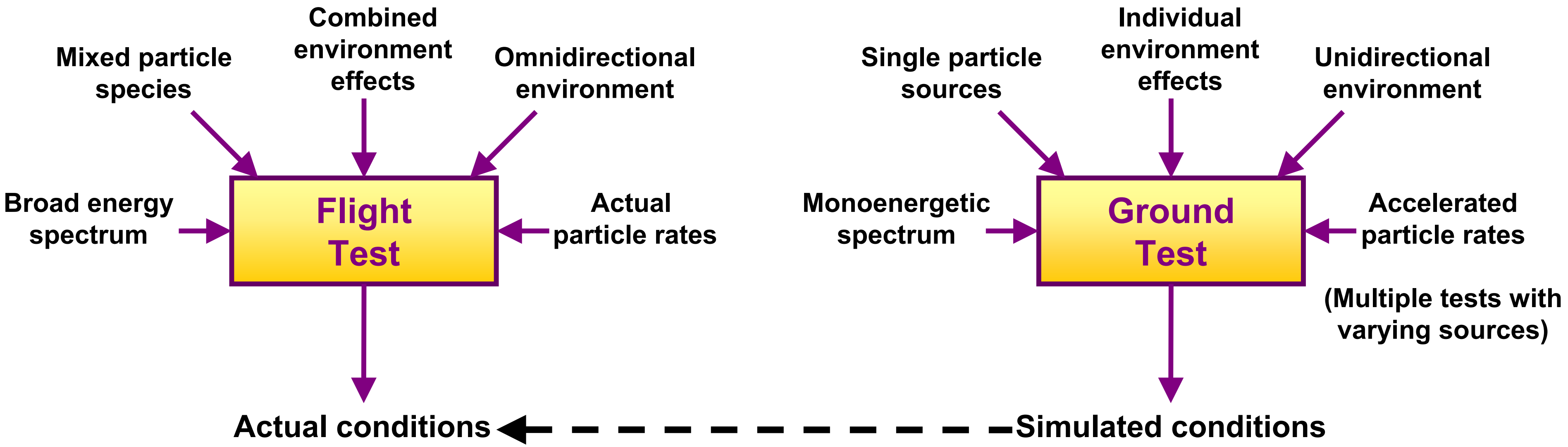
Evaluate Design/Component Usage

- Screen parts list
  - Use existing databases
    - RADATA, REDEX, Radhome, IEEE TNS, IEEE Data Workshop Records, Proceedings of RADECS, etc.
    - Evaluate test data
  - Look for processes or products with known radiation tolerance (beware of SEE and displacement damage!)
    - BAE Systems, Honeywell Solid State Electronics, UTMC, Harris, etc.
- Radiation test unknowns or non-RH guaranteed devices
- Provide performance characteristics
  - Usually requires **application specific** information: understand the designer's sensitive parameters
    - SEE rates
    - TID/DDD

System Radiation Test Requirements

- **All** devices with unknown characteristics should be ground radiation tested (TID and SEE)
- All testing should be performed on flight lot, if possible
- SEE testing should mimic or bound the flight usage, if possible

Radiation Test Issues - Fidelity



How accurate is the ground test in predicting Space Performance?

Test Requirements - TID

- All non-RH electronic/optic devices should be lot tested
  - Typically utilize STANDARD test methods as outlined in MIL 1019.5
    - Includes options for low dose rate testing and ELDRS
    - What do we do about mixed signal devices like BiCMOS processes?
  - Test levels should exceed requirement (with RDM)
    - Dose rate issues and annealing issues should be minimized
    - Units: Dose in krads (material)

Test Requirements - DDD

- Potentially required for
  - instrument detectors such as CCDs, APS, etc.,
  - optoelectronics such as optocouplers,
  - solar arrays,
  - linear devices, and others
- Must understand
  - predicted environment must be mapped to the test facility used
    - monoenergetic proton or neutron test versus the actual space environment
    - JPL currently recommends mapping to a 50 MeV proton equivalent
      - However, mapping function is not clearly understood or available for all materials especially compound semiconductors
    - Solar array typically use 1 MeV equivalents
- RDMs must be included at test levels
  - Units for test: Fluence in particles/cm^2 for a given energy

Test Requirements - SEE

- All non-SEE (not just RH) hardened devices should be lot tested
  - Some manufacturers assume TID hard covers SEE needs
    - Ex., we use ACTEL's RH1280 FPGA as a particle detector for test trips!
- Determine if heavy ion, proton, or both types of test are needed
  - Appropriate test levels must include sample size, particle, and fluence
- Make sure the test covers the actual application
  - ***Worst-case issues should be included***

“Engineer” with Designers

- Recommend alternate parts that meet performance requirements
- Recommend mitigation schemes
  - TID: detailed shielding analysis, additional shielding, box/board location, redundancy,...
  - DDD: shielding less effective at mitigating, but may help some
  - SEE: error detection and correction (EDAC) schemes, redundancy, voting,...
- Validate “acceptable” performance
  - E.g., SEU rates
    - By test
    - By simulation or circuit analysis
    - By determining SEU rate and managing risk
      - I.e., is the probability/risk of observing an SEU sufficiently low?
        - » e.g., a SEU rate of 1 per 10 years for a 1 month mission

Iterate Process as Necessary

- Spacecraft structure, box positioning, parts lists, etc. often change during mission development
- Mission requirements may change forcing redesign
- New information sometimes is discovered
  - E.g., Enhanced Low Dose Rate Sensitivity (ELDRs) effect in linear devices, DDD in optocouplers
  - If the design/development is more than a few months, new knowledge is sometimes obtained making “old parts, new issues”

Mitigating Radiation Effects in Electronics

Radiation Risk Management: Levels of Hardening

- Transistor/IC*
- Circuit design/board*
- Subsystem and system
- Satellite systems (constellations)

***Emphasized in this talk**

IC Hardening (1 of 2)

- Implies building an IC that meets system radiation requirements (call this a rad-hard or RH device)
- Features may include:
  - TID hardness or SEL immune process
  - Hardened transistors
  - Adding guard rings
  - Internal redundancy/voting
  - Internal error correction, etc.

IC Hardening (2 of 2)

- Advantages
  - Simplifies system design to meet radiation requirements
- Challenges
  - Performance, Cost, Schedule
- Examples
  - Hardened process
  - Compiled or hardened library design (hardness by design techniques)

Circuit Hardening (1 of 2)

- Implies adding radiation mitigation external to an IC
  - Shielding
  - RC filter
  - Voting logic
  - Error detection and correction (EDAC) codes
  - Watchdog timers, etc.
- Maybe be implemented or controlled by either hardware, software, or firmware

Circuit Hardening (2 of 2)

- Advantages
  - Allows use of higher (non-radiation) performance ICs
    - Faster processors
    - Denser memories, etc…
- Challenges
  - Adds complexity (cost and schedule?) to design
  - Often difficult to retrofit if problem is discovered late
    - Modification to flight hardware

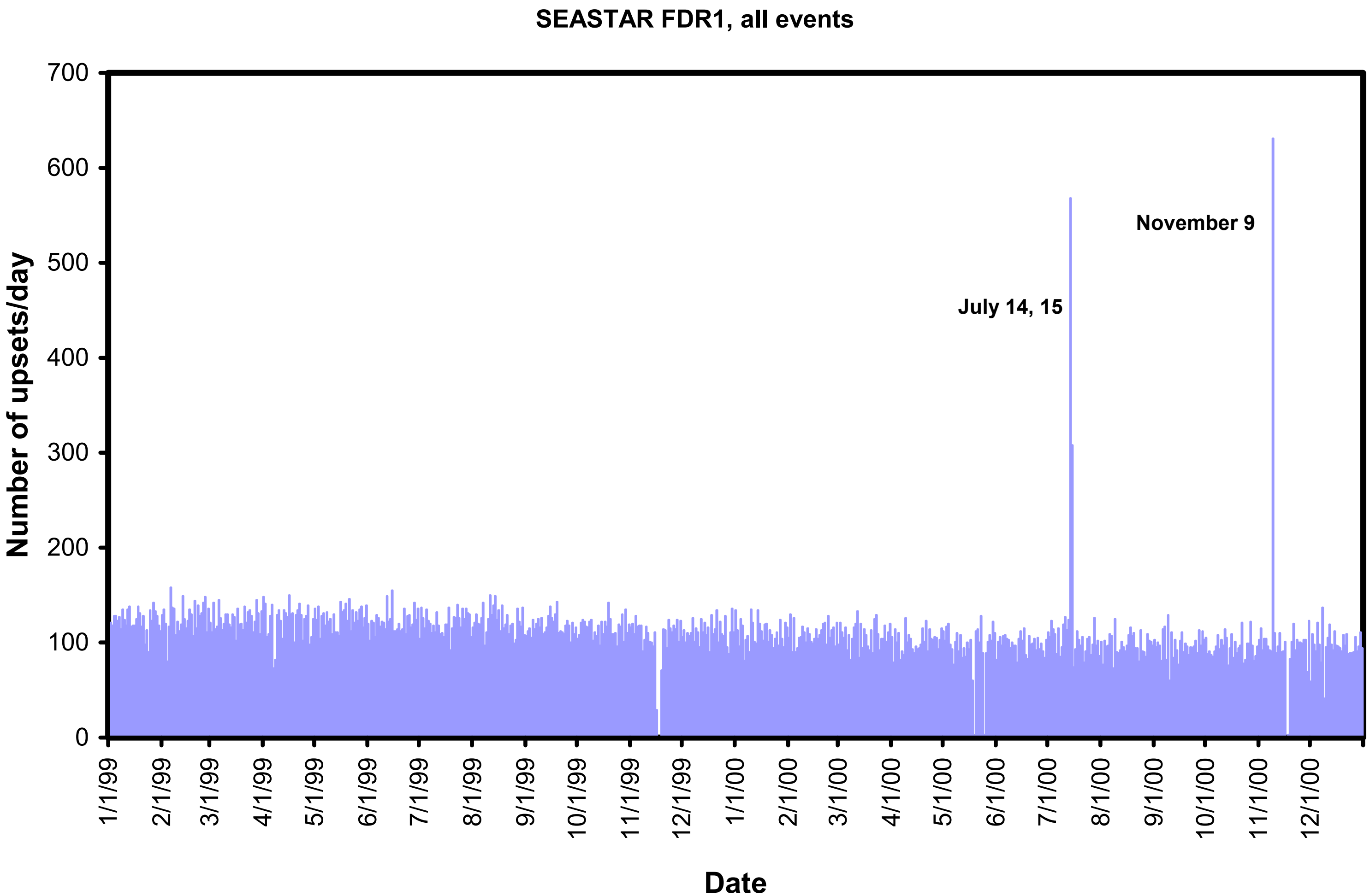
Mitigation of SEUs

- Three types of SEUs
  - Data (Ex., bit-flip to a memory cell or error on a communication link)
  - Control (Ex., bit-flip to a control register)
  - Transient (noise spike that may or may not propagate)
- Some overlap: Ex., RAM with program memory stored inside

Data SEUs - Sample Error Detection and Correction (EDAC) Methods

EDAC Method	EDAC Capability
Parity	Single bit error detect
Cyclic Redundancy Check (CRC)	Detects if any errors have occurred in a given structure
Hamming Code	Single bit correct, double bit detect
Reed-Solomon Code	Corrects multiple and consecutive bytes in error
Convolutional Code	Corrects isolated burst noise in a communication stream
Overlying Protocol	Specific to each system. Example: retransmission protocol

SeaStar Flight Data Recorders (FDRs) SEU Counts



Control SEUs - Sample EDAC Schemes

- Software-based health and safety (H&S) tasks
- Watchdog timers
- Redundancy
- Lockstep
- Voting
- IC Design techniques
- “Good engineering practices”
- Improved Designs (i.e., noise margins, method of sampling, etc.)

Transient SEUs (Single Event Transients – SETs)

- Examples of issue
  – ADCs, Analog, and Optical Links are among the device types affected
  – Optocoupler transients in HST and Terra (and IRIDIUM!)
  – Linear devices such as LM139 analog comparator (MAP, MPTB)
- Most commonly mitigated by
  – Filtering techniques
  – Over-sampling
  – High-speed device with a slow response following circuit

Destructive Conditions - Mitigation

- Recommendation 1: **Do not use devices that exhibit destructive conditions**
- Difficulties:
  - May require redundant components/systems
  - Conditions such as microlatch difficult to detect
- Mitigation methods
  - Current limiting
  - Current limiting w/ autonomous reset
  - Calibration of device
- **MANY DESTRUCTIVE CONDITIONS MAY NOT BE MITIGATED**

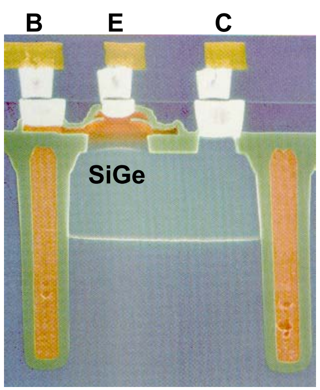
Discussion: Mission Implications

- Regardless of the orbit and mission duration
  - Planning for tolerance should be done early in mission design and development
- Example:
  - Adding spot shielding to reduce TID requirements
    - Mechanical layout must accommodate this addition
      - Mounting, vibration, thermal, schedule, cost,…
- Bottom line: Harden while you design, not after

Ground-based Radiation Effects Research: Recent Highlights

SiGe Technology Flowdown - Technology Development

Technology Development



DARPA and DoD have invested >$100M in the development of SiGe Technology at IBM and elsewhere

- **High-speed (approaching 100 Ghz)**
- **Low noise**
- **Low power consumption**
- **Mixed signal capabilities**
- **Standard Si compatible**

NASA has keen interests

- **RF/Microwave/Communications**
- **Mixed signal/System-on-a-chip**
- **Ultra-high speed data transfer**
- **Low-noise instrumentation**
- **Potential extreme temperature applications**

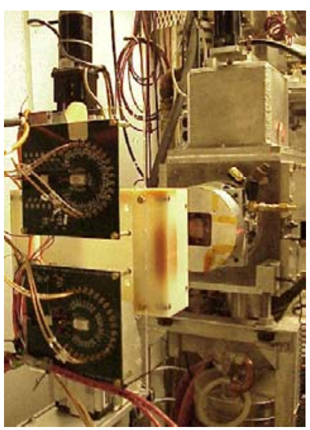
SiGe Technology Flowdown - Ground Test

Technology Development

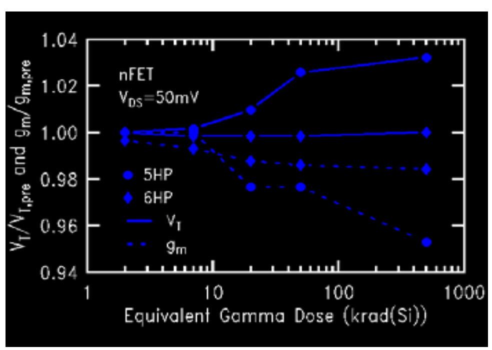
Ground Test Protocol Development

The ERC Project along with DoD is in process of developing technology radiation sensitivity models

- **Dose and damage tests have been performed with encouraging results**
- **Preliminary single event data indicates a single event sensitivity. FY01/02 plans focus on single event testing, modeling, and hardening**
- **Test protocols available NLT FY03**
- **NEPP Program also supporting reliability modeling of SiGe**



Proton irradiation test fixture



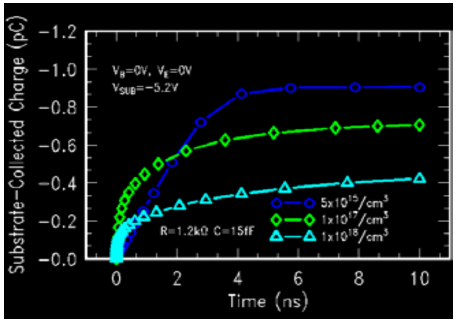
SiGe Damage Data

SiGe Technology Flowdown - Tools

Technology Development

Ground Test Protocol Development

Technology Application Model/Engineering Tool Development

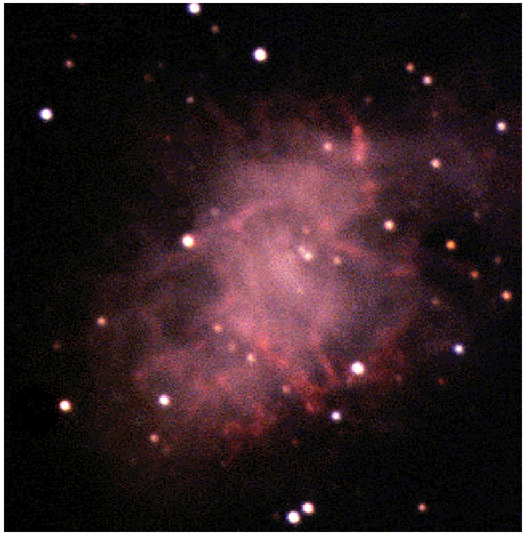


SiGe Charge Collection Modeling

Upon completion of ground test protocol development, predictive performance tools are greatly desired

- **Modules for single event upset (SEU) for industry standard software (CREME 96)**
- **SEU-hardened cell library**

Detector Technology Flowdown - Technology Development



CCD Messier image

Detector technologies have been critical to increased science knowledge for NASA

- **Examples include Hubble Space Telescope's charge coupled device (CCD) based instruments. Newer Si-based CCDs have scaled geometries allowing better image resolution.**
- **Wavelengths of interest include visible, x-ray, ultraviolet, and infrared**
- **Engineering applications include star trackers and star cameras**

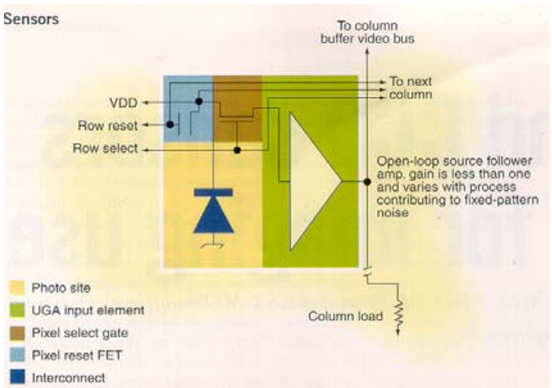
Technology limitation: performance in the space radiation environment

- **DoD and NASA have invested in hardened sensor technologies for space utilization (p-channel CCDs and monolithic advanced pixel sensors (APS))**

Detector Technology Flowdown - Ground Radiation Test

Technology Development

Ground Test Protocol Development



Schematic representation of an advanced pixel sensor

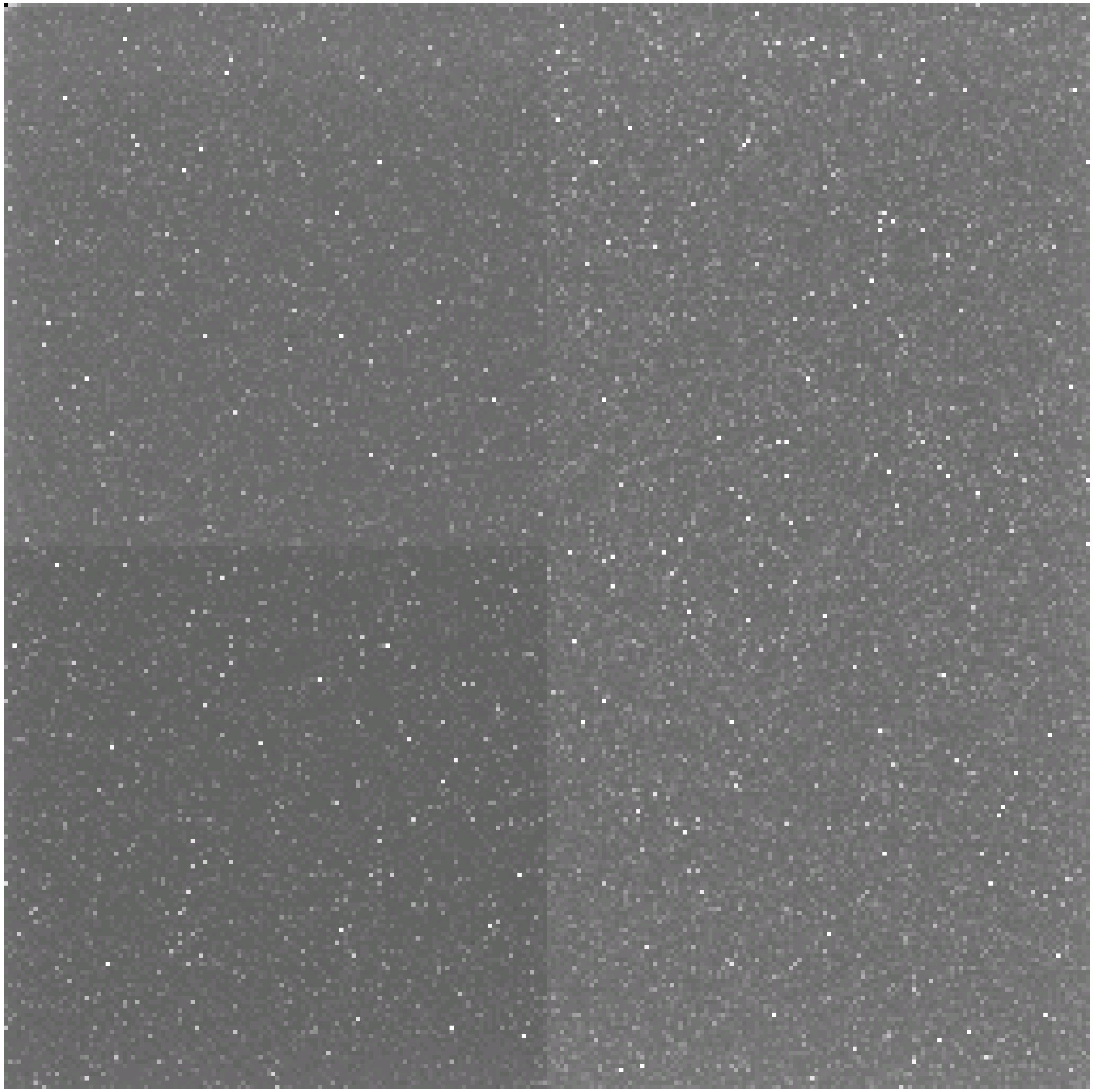
While many detectors and detector-based instruments have been tested and calibrated prior to flight, there is no community-wide test standard

- **NASA (ERC) and DoD have begun collaborations which will lead to a "lessons learned" overview of ground testing.**
- **In some areas, test data is limited or old. A relevant example is ground test data for determining cosmic ray rejection in images.**

Ground tests of newer technologies may or may not be able to leverage on older data

- **Flight performance has rarely matched predicted models (AXAF, HST, SOHO, et al)**
- **Shortcomings may be due to technology or shielding models or mapping of the flight environment to the ground test environment**

An APS Under Heavy Ion Irradiation



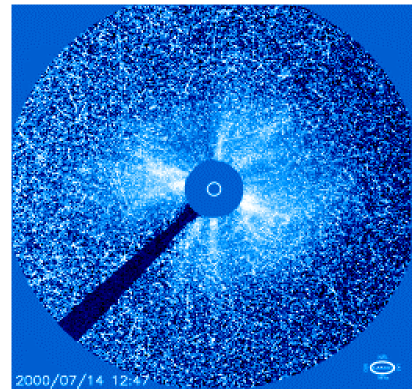
4 quadrants;
4 circuit
designs

Detector Technology Flowdown - Tools

Technology Development

Ground Test Protocol Development

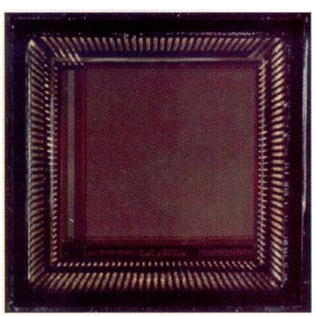
Technology Application Model/Engineering Tool Development



SOHO/LASCO coronograph spotted with solar particles during July 14, 2000 event

Upon completion of ground test protocol development, predictive performance tools are greatly desired

- **Modules for image degradation due to radiation damage**
- **Methods for cosmic ray rejection**
- **Methods for damage hardening**

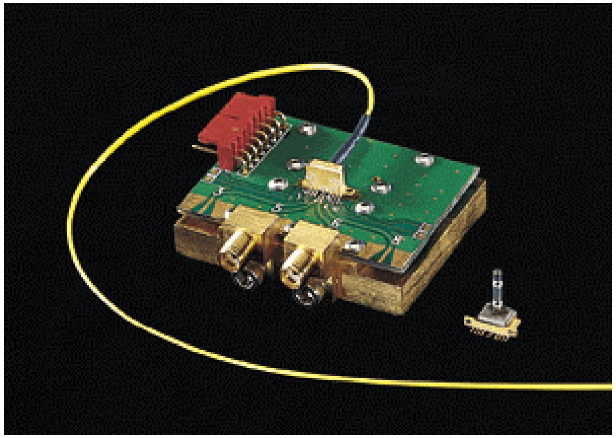


Advanced column sensor array

Fiber Optic Links (FOLs) - NASA Interest

- NASA has pioneered the use of FOL technology since the early 1990's and the insertion of NASA-developed MIL-STD-1773 hardware was flown on the first Small Explorer (SMEX) mission
  - Other missions including ISS have/will be relying heavily on FOL technology for both bus and payload applications
- Fiber or free-space optical link plans are emerging in NASA, DoD, and commercial space worlds
  - Benefits in bandwidth, weight, power, EMI/EMC, etc are prime advantages
- ***Radiation effects knowledge immature relative to microelectronics area: draft guideline available under NEPP/ERC***

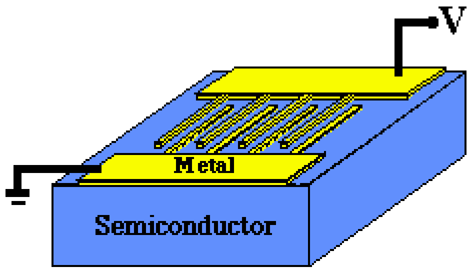
Microelectronics and Photonics Test Bed



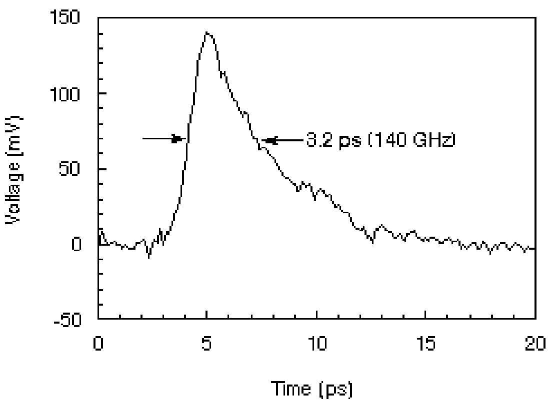
Space Radiation Effects Issues for Fiber Links

- Issues include:
  - Darkening in passive optical components (fibers, lenses, etc.)
    - Choices may be made to minimize concerns such as the use of pure silica fiber and not using graded index (GRIN) lenses
  - DDD in active components
    - Primarily driven by proton fluences encountered and choice of technology (Si, GaAs)
  - Support electronics
    - May drive system tolerance to radiation effects
  - ***Single proton (particle) effects in receivers***
    - Causes bit errors in data stream (i.e. increases, bit error rate or BER)
  - Mitigation of Single Proton Effects in Receivers
    - Choice of detector: III-V direct bandgap @ higher wavelengths vs. Si (or similar) indirect bandgap
    - Circuit hardening approaches
    - System level solutions

Metal Semiconductor Metal (MSM) Detectors



A metal-semiconductor-metal (MSM) photodetector



3.2 ps, 140 GHz MSM photodetector on silicon-on-insulator (SOI)

http://www.tc.umn.edu/nlhome/m017/nanolab/research/photodetect/photodetect.html

Prime Driver:

Terrestrial communication (telephone, internet, …)

Advantages:

High-speed photodiode with lower power consumption
Monolithic integration with FET possible
Available in multiple wavelengths

May:

Allow true monolithic receiver

Applications:

Commercial fiber links such as ethernet, fibre channel (FC), …
Hardened systems

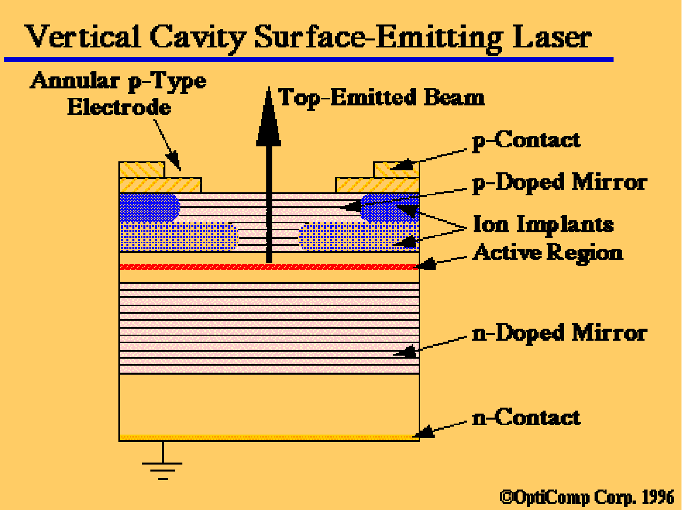
Radiation Issues:

Results are encouraging

- TID tolerant
- Some SEU sensitivity

Vertical Cavity Surface Emitting Laser (VCSELs)

Alternative to current edge-emitting lasers and LEDs



Sample VCSEL

Advantages:

Lower power consumption and reduced mass
High aggregate throughput
Integration (monolithic) with detectors and electronics

May:

Provide a "fiber-less" system

Applications:

Wavelength division multiplexing (WDM) for high throughput systems
Smart pixel array (SPA) systems
Commercial (terrestrial) data links

Sample Developments:

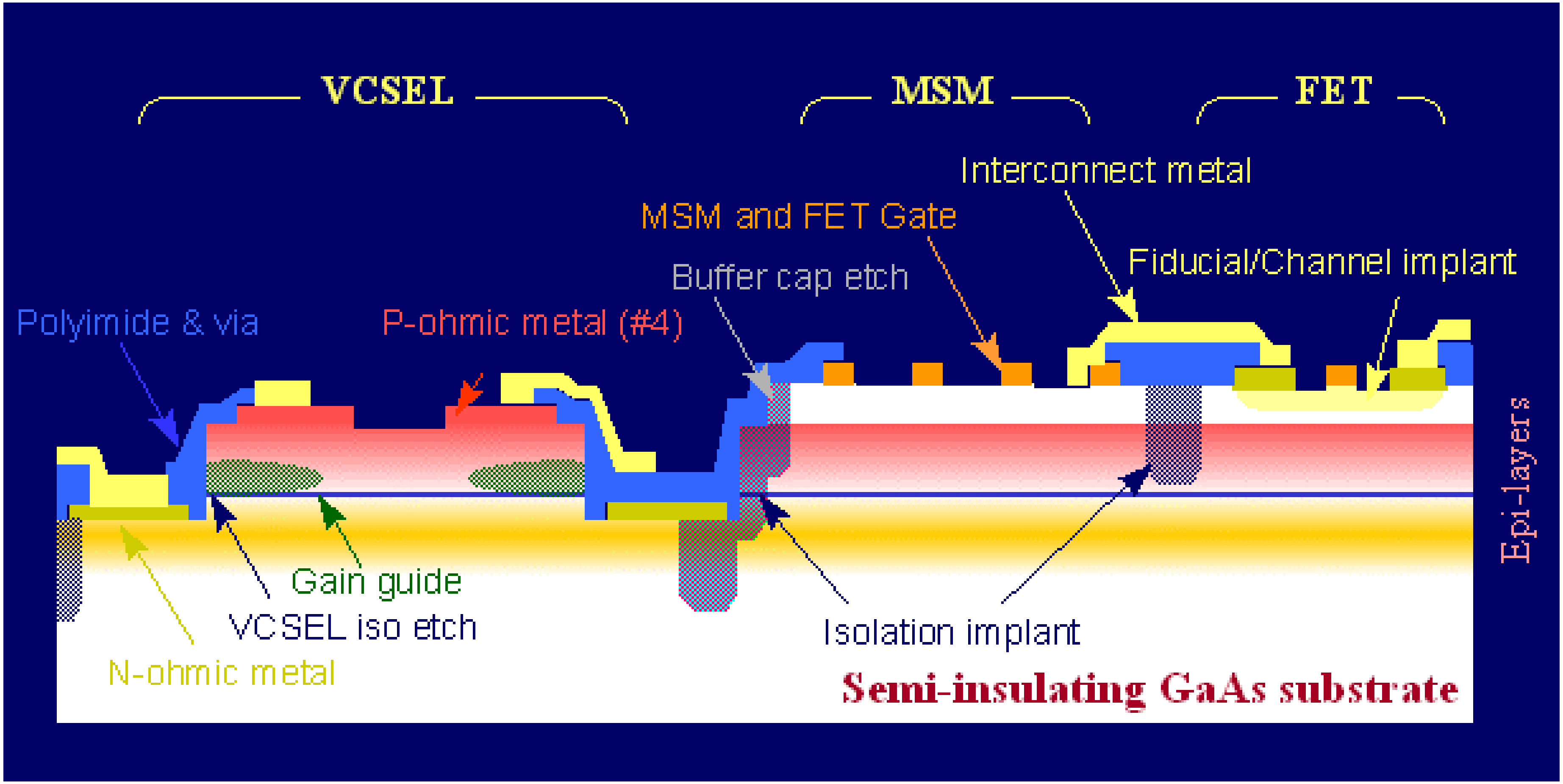
HP VCSEL ethernet
Honeywell's flyable link

Radiation Issues:

Data looks promising

VSCELs and MSMs Integrated on a Single Substrate

Schematic Cross Section of the Integrated Device Structures



Trend is to form a true monolithic optoelectronic IC (OEIC)

http://co-op.gmu.edu/vcsel/oechip.html

Applications of VCSEL-Based Smart Pixel Arrays

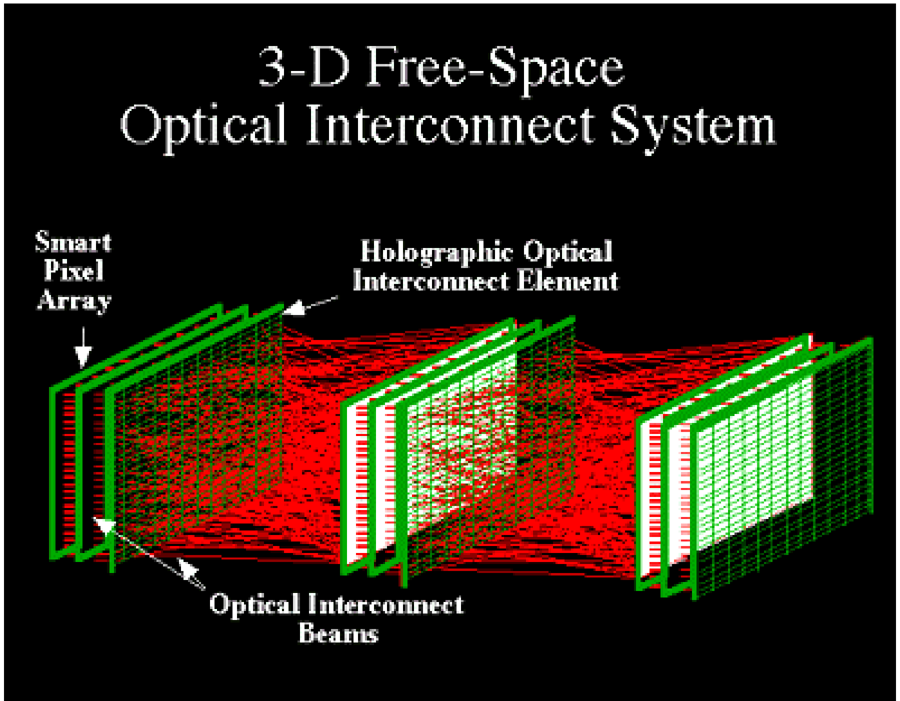


Figure 2.3.2

3-D system based on smart pixel arrays (SPAs) and holographic optical interconnect elements (HOIEs). Each SPA element consists of a VCSEL transmitter, photo-receiver, and a 1-bit microprocessor. The HOIEs enable global connectivity (connection between any transmitter and any receiver on adjacent arrays).

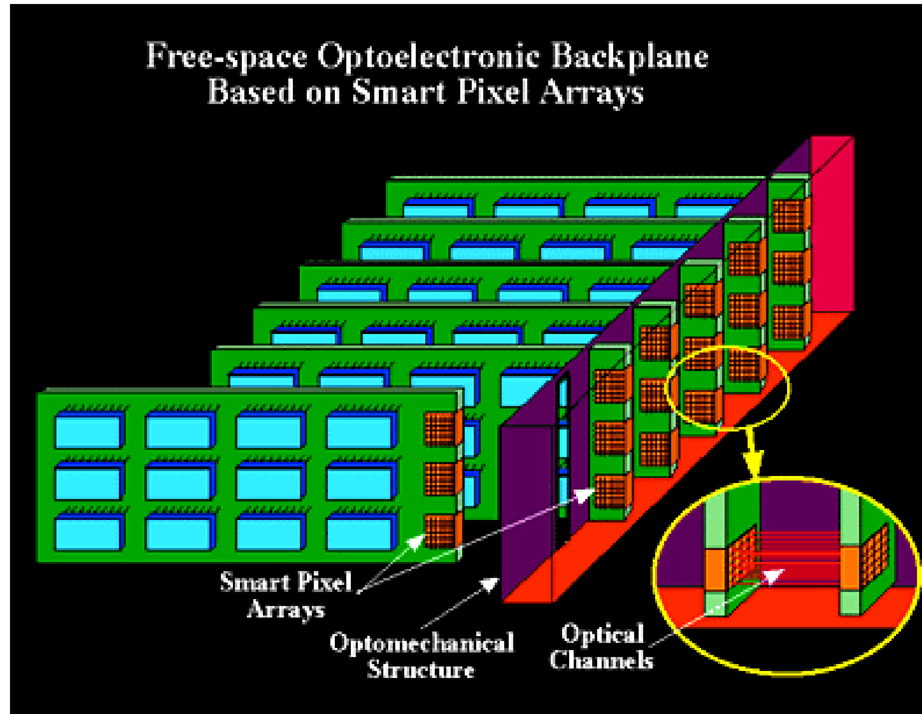
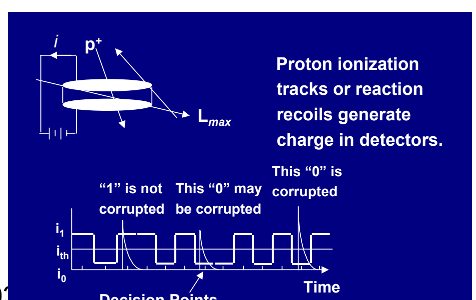


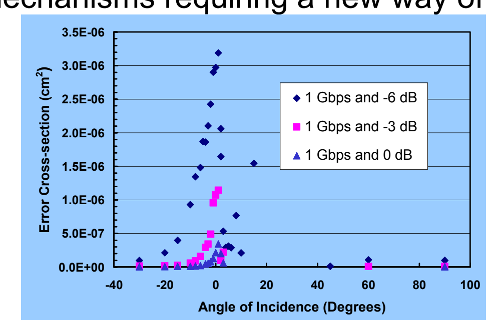
Figure 2.3.1 Optical Backplane based on optically inconnected smart pixel arrays (SPAs). Each element of the SPAs consists of a VCSEL transmitter, photo-receiver, and a 1-bit microprocessor.

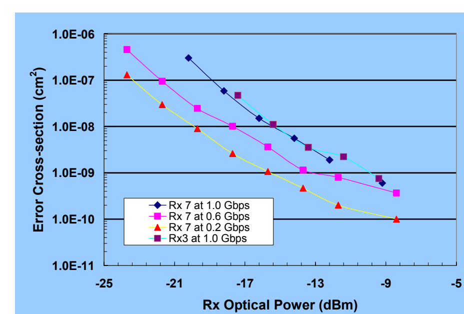
http://www-ocs.colorado.edu/~berto/nsf/research.html

FOL - Result Highlights

- Prime issue is single event transient (SET) propagation into effective FOL bit error rate (BER)
- Hardware developed in the early 1990s with slower bandwidth allowed for re-transmission of corrupted data.
  - This is NOT a feasible solution for higher speed systems
- DTRA has partnered with NASA on this task
- High-speed (>100 MHz to > 1 GHz) FOLs and detector technologies evaluated
  - Commercial systems as well as a “Ruggedized” link provided by Honeywell (DoD-funded)
- Proton SEE tests indicate errors are related to:
  - Data rate
  - Optical power in system (I.e., receiver sensitivity and received optical power)
  - Particle energy and angle of arrival
    - Indicates mixed SEE mechanisms requiring a new way of testing and predicting SEE performance

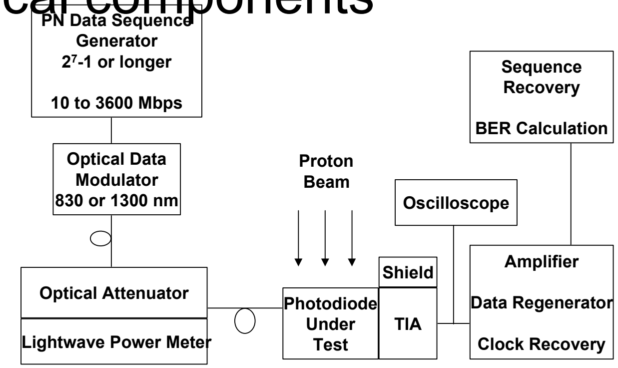


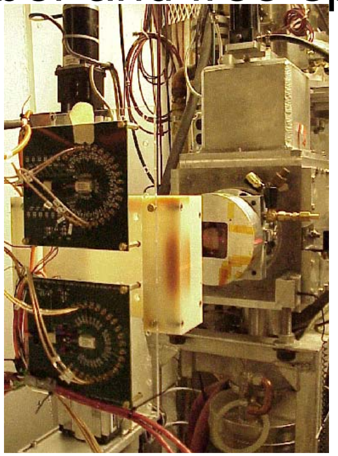




FOL - FY02 and Beyond

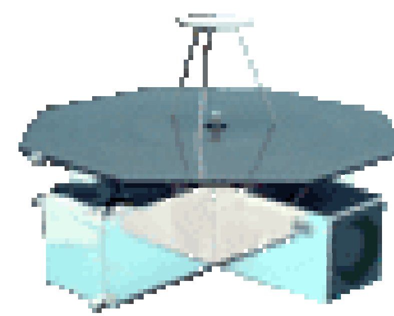
- FY02 efforts are focused on developing
  - Completing lessons learned to date: draft available
    - A critical look at predictive tool that utilizes the lessons learned to enable improved prediction of space performance for NASA flight projects
  - Lessons learned for proton SEE testing (extends beyond FOL)
- Testing performed with DoD (China Lake - NAVAir) on 10 Gbps serial FOL being developed for avionics applications
- Out-year plans to expand to exotic-doped fiber and free-space optical components





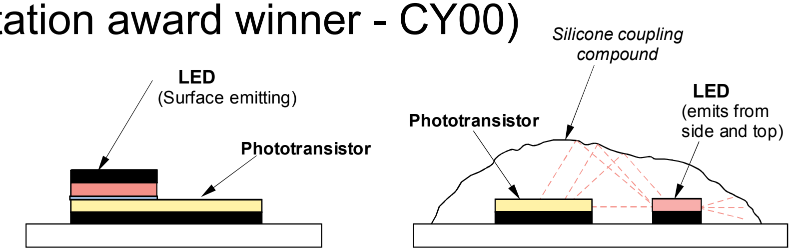
Optocoupler Radiation Background

- Two in-flight anomalies in recent years have sparked extensive investigation of optocouplers and their usage in NASA flight projects
  – TOPEX: Device failure traced to displacement damage (non-ionizing effects of radiation)
  – Hubble Space Telescope (STIS/NiCMOS): Single particle induced transients forced a change in operations and some loss of science data
- The ERC Project has been focused on determining
  – Failure mechanisms of optocouplers,
  – NASA Test Methods for optocouplers, and
  – NASA Applications Guidelines for optocouplers



Optocoupler Radiation Assessment Approach and Results

- ERC gathered interagency partnering with Defense Threat Reduction Agency (DTRA), Sandia National Laboratories (SNL), and others to evaluate these two issues
- Results:
  - Failure mechanisms determined:
    - Displacement damage results (best paper award winner at IEEE NSREC - CY99)
      - LED versus photodiode sensitivity
      - Effect of proton energy and mapping of energy to space environment
      - Annealing, temperature, and lifetime effects
      - Effects of bias and application
      - COTS part-to-part variability
    - Transients
      - Determined complex relation of proton energy and angle of arrival showing both direct and indirect ionization mechanisms on photodiode
      - Heavy ion tests indicate secondary transients at higher LETs caused by electronics
  - Optocoupler radiation test data compendium published in IEEE Radiation Effects Data Workshop (best presentation award winner - CY00)

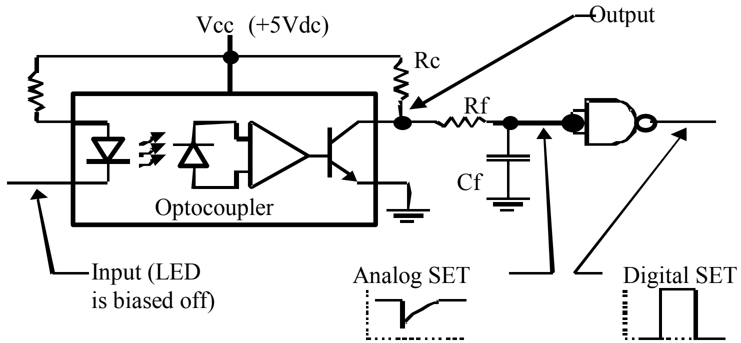


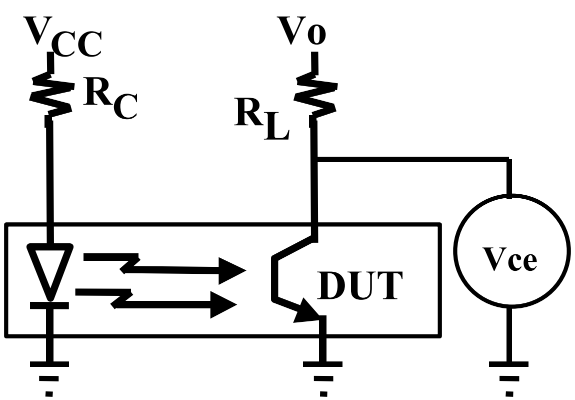
(a) Sandwich structure (direct coupling to detector)

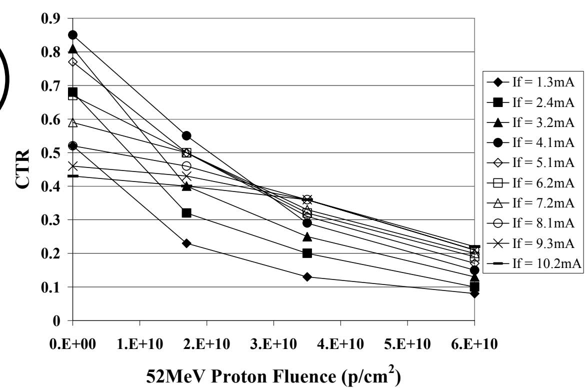
(b) Lateral structure (reduced coupling efficiency)

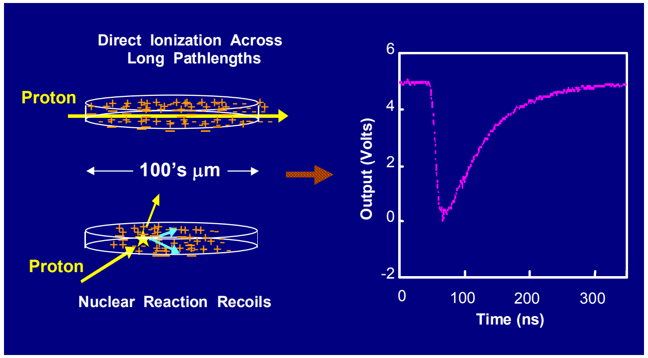
Optocoupler Plans for FY01-FY02

- FY01 is the culmination of 5 years of research into these issues
- Deliverables
  - NASA Test Methods for Optocouplers
  - NASA Guideline for Assessing Application of Optocouplers to a Mission-specific Scenario
- Final documents due in FY02



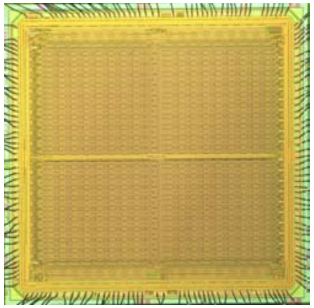


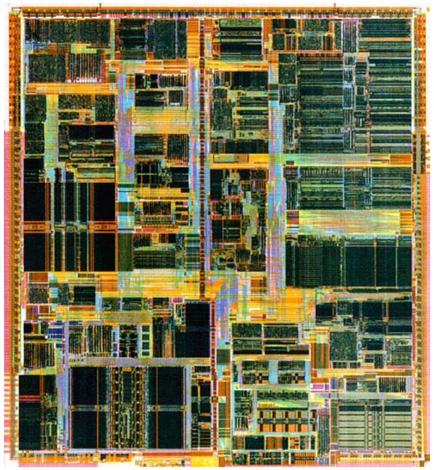




Radiation Evaluation of COTS Microelectronics

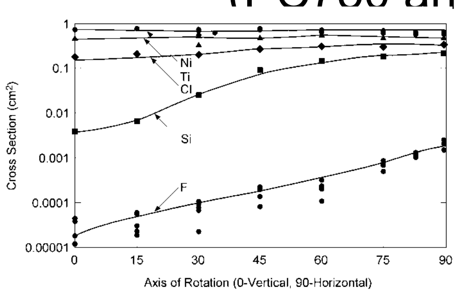
- This task has focused on providing a large number of radiation characterizations of new COTS microelectronics, thus allowing designers information on much needed components prior to insertion into design
- Types of microelectronics evaluated include
  - Field programmable gate arrays (FPGAs)
  - DC-DC Converters (28V and 120V busses)
  - Analog-to-digital converters (high-speed and standard)
  - SDRAMs
  - Microprocessors

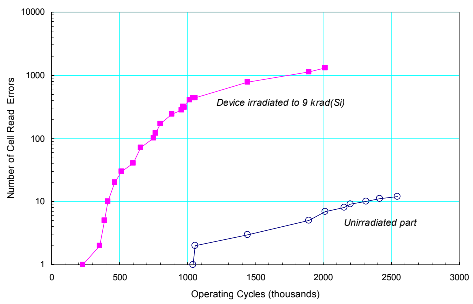


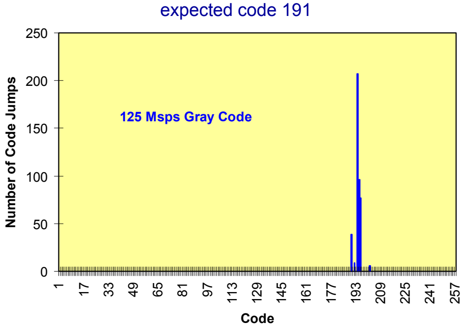


COTS Microelectronics Results

- ERC has partnered with semiconductor manufacturers and NASA flight projects in supporting new product introduction and designer needs
- Result highlights
  - Relative radiation softness of commercial DC-DC converters (SEGR, SET, TID)
  - Widespread range of radiation sensitivities of FPGAs (including collaborative evaluation of commercial device hardening by ACTEL Corp.)
  - Determined radiation test issues with SDRAMs (particle arrival angular effect that did not match traditional test methods)
  - Determined new single event latchup screening techniques for ADCs
  - Provided first radiation effects data on advanced microprocessors (PC750 and Pentium III)



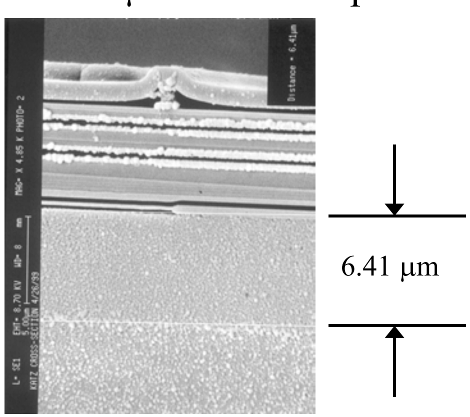




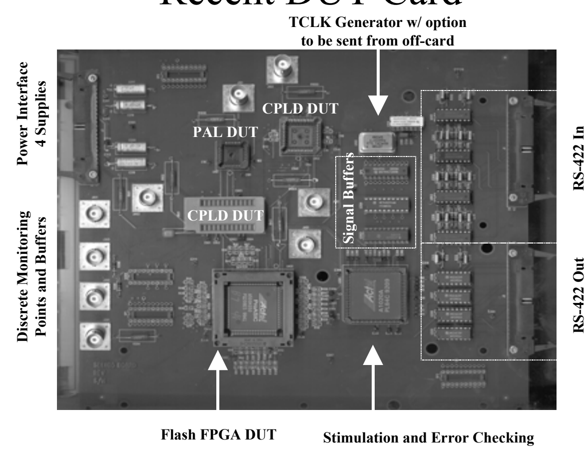
COTS Plans for FY01-FY02

- ADCs
  - Develop agile input test method for single event testing of high-speed (>1 Ghz) devices (partnered with NRL, DTRA, NRO)
- Microprocessors
  - Continue evaluation of state-of-the-art devices
  - Develop a NASA Standard Test Method for SEE Testing of Microprocessors
- DC-DC Converters
  - Support radiation testing of 120V DC-DC converters that failed original tests for ISS/ECLSS at MSFC but are being modified (replacement of power MOSFET)
- Continue numerous other characterizations

0.35 µm FPGA - Epi



Recent DUT Card



Final Comments

Radiation Resources at GSFC

- Flight Electronics and Radiation Effects Branch
  - POCs: Ken LaBel or Janet Barth (Ass. Branch Head)
    - Radiation Effects and Analysis (REA) Group
      - Effects/Technology
    - Radiation Physics Office (RPO)
      - Environment/Modeling
    - Jointly provide full systems engineering radiation support for flight projects
- **http://radhome.gsfc.nasa.gov**
- **http://nepp.nasa.gov**